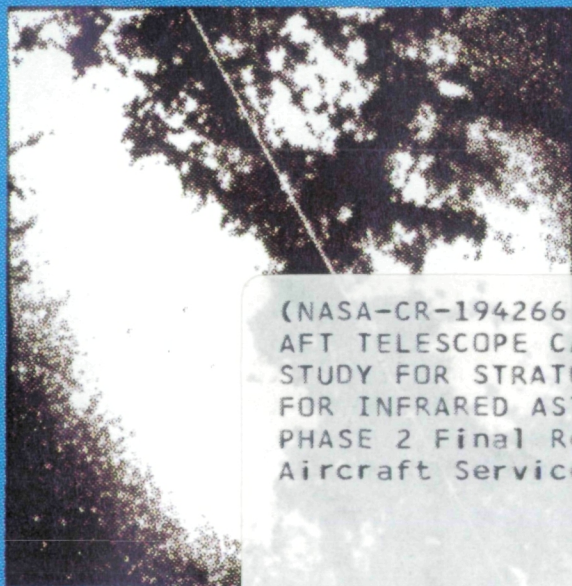
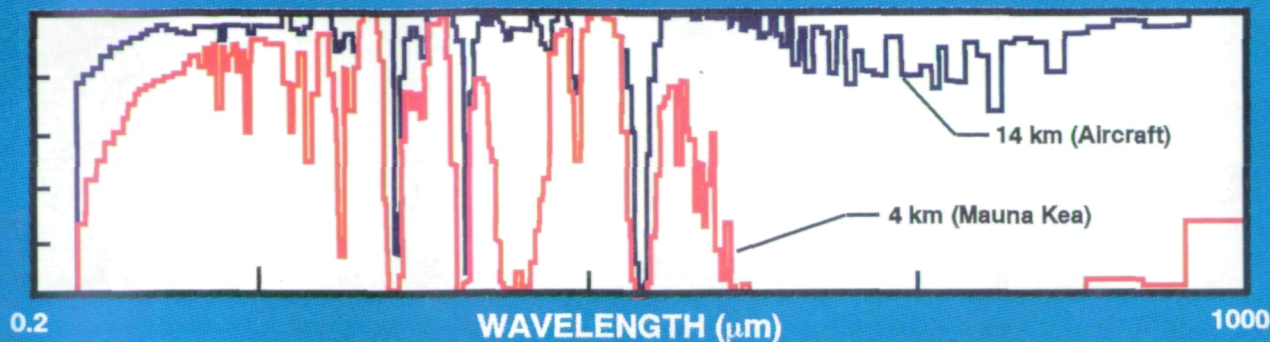


SOFLIA

NASA-CR-194266

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TRANSMISSION

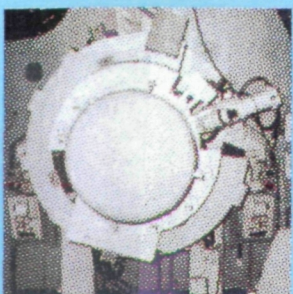


(NASA-CR-194266) AIRCRAFT SYSTEM
AFT TELESCOPE CAVITY CONFIGURATION
STUDY FOR STRATOSPHERIC OBSERVATORY
FOR INFRARED ASTRONOMY (SOFIA),
PHASE 2 Final Report (Lockheed
Aircraft Service) 171 p

N94-29685

Unclas

H1/05 0003851



Phase II Final Report
Aircraft System Aft Telescope Cavity Configuration
Study for Stratospheric Observatory for
Infrared Astronomy

 **Lockheed Aircraft Service Company**

**AIRCRAFT SYSTEM
AFT TELESCOPE CAVITY
CONFIGURATION STUDY
FOR
STRATOSPHERIC OBSERVATORY
FOR INFRARED ASTRONOMY**

SOFIA

**PHASE II
EXECUTIVE SUMMARY**

CONTRACT NO.:NAS2-13872

SOFIA PHASE II EXECUTIVE SUMMARY

INTRODUCTION

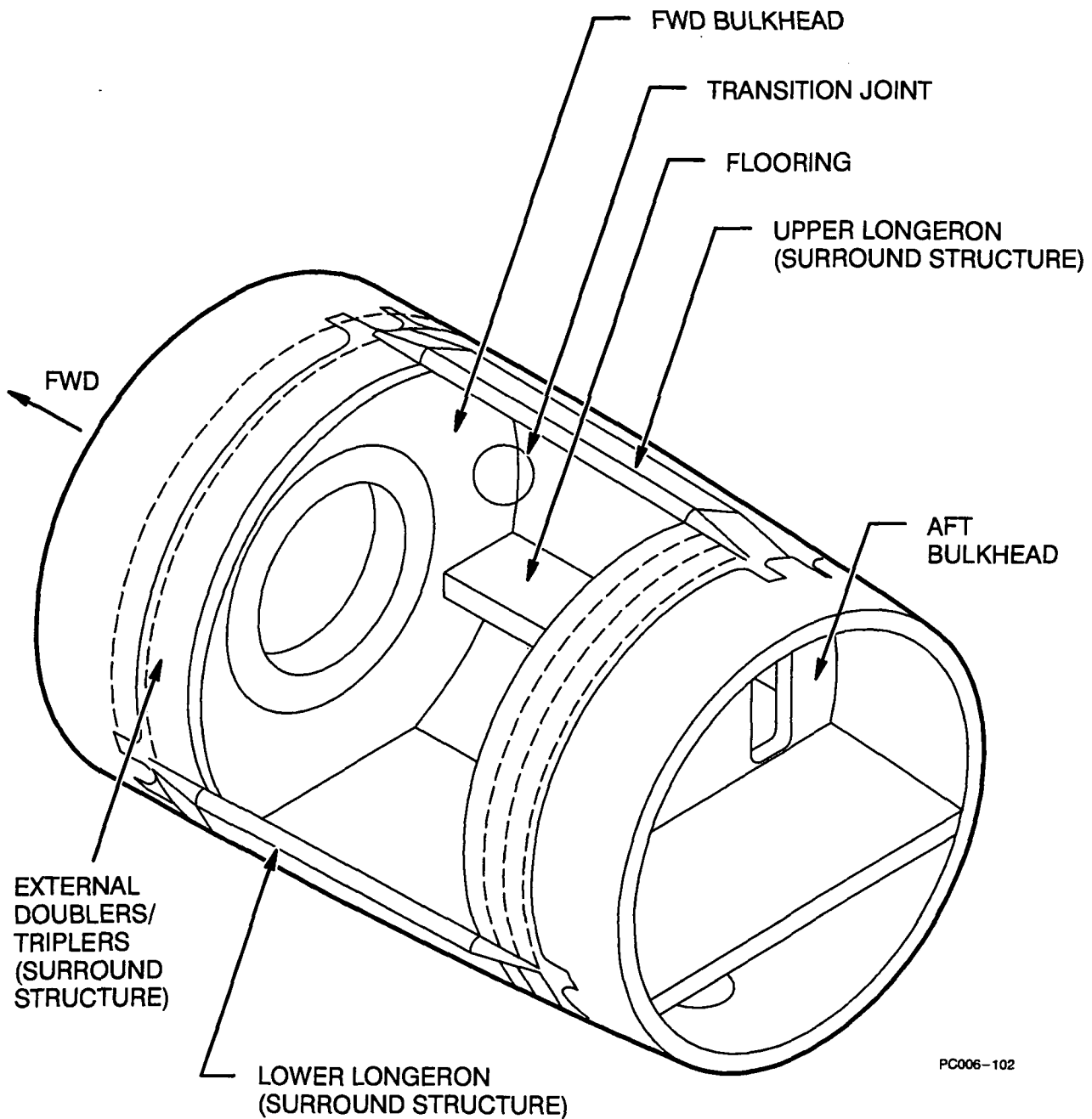
The SOFIA Aircraft System (AS) Phase I Study was a broad-based study which addressed itself to satisfying technical and programmatic requirements by drawing from existing technology and applying cost-efficient commercial approaches to the aircraft modification.

In this SOFIA AS Phase II Study, five (5) critical areas of the aircraft were selected for more detailed investigation. These are:

- Forward Pressure Bulkhead
- Aft Bulkhead
- "Free" Shell to Bulkhead Interface
- Shell Cut-out Surround Structure
- Flooring

The in-depth investigation of these areas upon a Finite Element Model (FEM), with a Fine Grid Model in areas of particular interest. The FEM code used is called "STRAP" and was developed by the engineering firm Rasmussen and Associates. STRAP is NASTRAN compatible to within 1%. The loads applied to the model were approximated from known 747 envelope conditions. The areas of investigation, and a section through the fuselage is shown on pages ii and iii.

The thrust of this investigation was to develop the design concepts conceived under phase I to the point where detail design could be undertaken with a high confidence level.



PRINCIPAL AREAS OF STUDY AFT CAVITY LOCATION
SOFIA PHASE II



FORWARD PRESSURE BULKHEAD

This bulkhead forms the aft boundary of the pressurized portion of the fuselage and provides primary support for the Telescope assembly. It also forms the forward wall of the telescope cavity.

The bulkhead is constructed of twelve built-up 20 inch deep beams, four oriented vertically, four horizontally, and four on the diagonal. At the intersections the beams are spliced using cap slice plates and "bathtub" fittings. These beams support a flat extruded pressure web with bulb risers facing aft into the cavity. An extruded "Tee" section cap provides the web to fuselage skin attach member.

The bulkhead is stiffness critical as a result of a criteria of 0.5 inch deflection at the telescope mount points. The member sizes required to achieve this stiffness result in low stress levels for all the applied load conditions.

AFT BULKHEAD

This bulkhead is of similar construction to the forward bulkhead although of less massive proportions as it does not have to resist the cabin pressure loads and carry the weight of the telescope. It does however carry the telescope brake, a spring/hydraulically operated device, and so is "tuned" to the stiffness of the forward bulkhead to minimize brake stroke differences between the pressurized and unpressurized conditions. The bulkhead also contains a non-structural door for ground access to the telescope cavity from the aft fuselage.

BULKHEAD TO SHELL INTERFACE

The attachment of the forward bulkhead attach to the fuselage shell is a critical fatigue joint. The flat bulkhead rotates aft at the shell intersection and constrains the shell against expansion while forward of the bulkhead the shell expands normally under cabin pressure.

Intercostals of tailored stiffness to the shell at each twenty inch deep beam to provide a gentle transition from the bulkhead constrained shell to the "free" shell. Due to the critical nature of this joint a typical intercostal was modeled down to the fastener level. The detailed loads extracted from this model run were then used to calculate Stress Severity Factors (SSF) which, in turn, were used to determine a fatigue life for this typical joint. The intercostal was sized to give a predicted factored life of greater than 100000 cabin pressurization cycles.

CUTOUT SURROUND STRUCTURE

The purpose of the cutout surround structure is to restore the strength and stiffness lost due to the shell cutout. This is done by framing the opening with longerons and using the bulkhead caps and fuselage frames as the other framing members. Skin doublers and triplers are added to accommodate the increased shear flows and provide added stiffness and stability at the cutout edge. Due to the anticipated configuration of the NASA designed cavity door the primary longerons (the ones immediately adjacent to the cutout) are external to the fuselage and aerodynamically faired, the secondary longerons are internal. As the longerons are essentially unsupported between bulkheads, they require high moments of inertia, particularly the primary ones.

FLOORING

With the exception of a maintenance walkway the aircraft main deck floor is removed between the bulkheads to permit installation of the telescope. A walking surface is also added to the cargo floor.

Forward of the pressure bulkhead and aft of FS 1600 the floor is cut away between BL 60 L & R to permit installation of the telescope and provide comfortable access to the telescope instrument package. The retained portion of the floor has shear webs and fore/aft beams added to enable it to act as horizontal beams to hold the shell in the same shape as when it is tied across by floor beams.

The floor is also cut back from the bulkheads to permit their deflection without imposing loads on the floor structure.

CONCLUSIONS

Structurally the SOFIA program is very "doable". It can be achieved using standard aircraft materials and processes and does not require exotic materials to achieve its goal. As can be seen from the preceding section, stiffness is as much a driving force as strength. This does tend to make the structure rather heavy, but as the telescope assembly, support structure, and instrumentation package comprise most of the effective payload weight, this is not a significant problem for this aircraft.

Structurally the most problematic aspects of this program are:

- o Boeing unwillingness to furnish data, and hence the need to use a "back-door" approach, (a frequently used option in the after-market modification field).

Comment: This is not difficult to overcome although it will increase engineering costs.

- o Fatigue damage at the attachment of the flexible shell to the rigid bulkhead.

Comment: This can be addressed through attention to detail design and adequate component testing.

PROPOSED PHASE II STUDY TOPICS

As stated in the Conclusions section, the most problematic structural item is the bulkhead to shell joint. In light of this, a Phase III Study could address this issue with a detail design study coupled with a full scale fatigue test of the joint. Stringer fitting feed-throughs should be incorporated in the test item to provide a comprehensive fatigue assessment of the system.

A second and related study would be a detail design and fatigue test of the pressure bulkhead beam intersections.

LAS recommends these subject areas be included in a Phase III SOFIA Aircraft System study.

**AIRCRAFT SYSTEM
AFT TELESCOPE CAVITY
CONFIGURATION STUDY
FOR
STRATOSPHERIC OBSERVATORY
FOR INFRARED ASTRONOMY**

SOFIA

**PHASE II
FINAL REPORT**

CONTRACT NO.:NAS2-13872

ABSTRACT

This report furnishes the results of the Phase II study contract for the Stratospheric Observatory for Infrared Astronomy (SOFIA) as installed in a 747-100 aircraft.

The SOFIA mission requires the airborne telescope to be open to the atmosphere during observation periods and isolated from ambient conditions during pre-flight periods for cooling. These constraints require a large cut-out in the fuselage for viewing and bulkheads for support and isolation, both forward and aft, of the telescope. A closeout door is also required to isolate the cavity during the pre-cooling period. The design of this item has been retained by NASA.

This study is limited to five specific areas as defined by the statement of work, these being:

- i) Forward Bulkhead
- ii) Aft Bulkhead
- iii) Shell Cutout Surround Structure
- iv) Forward Bulkhead to Shell Transition
- v) Floor Structure

The criteria, assumptions, methodology, and results are described in the following sections and appendices.

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Appendix A	AIAA Paper No. 74-983 "Correlation of Analysis and Test Data to the Effect of Fastener Load Transfer on Fatigue" by B. L. Cornell and L.G. Darby	A.1

LIST OF REFERENCES

- 1) Drawing B54114000 "747-100 SOFA MODIFICATION"
- 2) Lockheed Structural Life-Assurance Manual
- 3) Report 1391-1 by G. S. Rasmussen & Associates "Preliminary Finite Element Modeling of B747-100 Aft Fuselage"
- 4) Lockheed Missiles and Space Company Report LMSC/P016023 "Stratospheric Observatory for Infrared Astronomy Final Review"
- 5) Fax Kunz (NASA) to Zoller (LAS) "Cavity Geometry Data" dated 12/15/93

1.0 INTRODUCTION

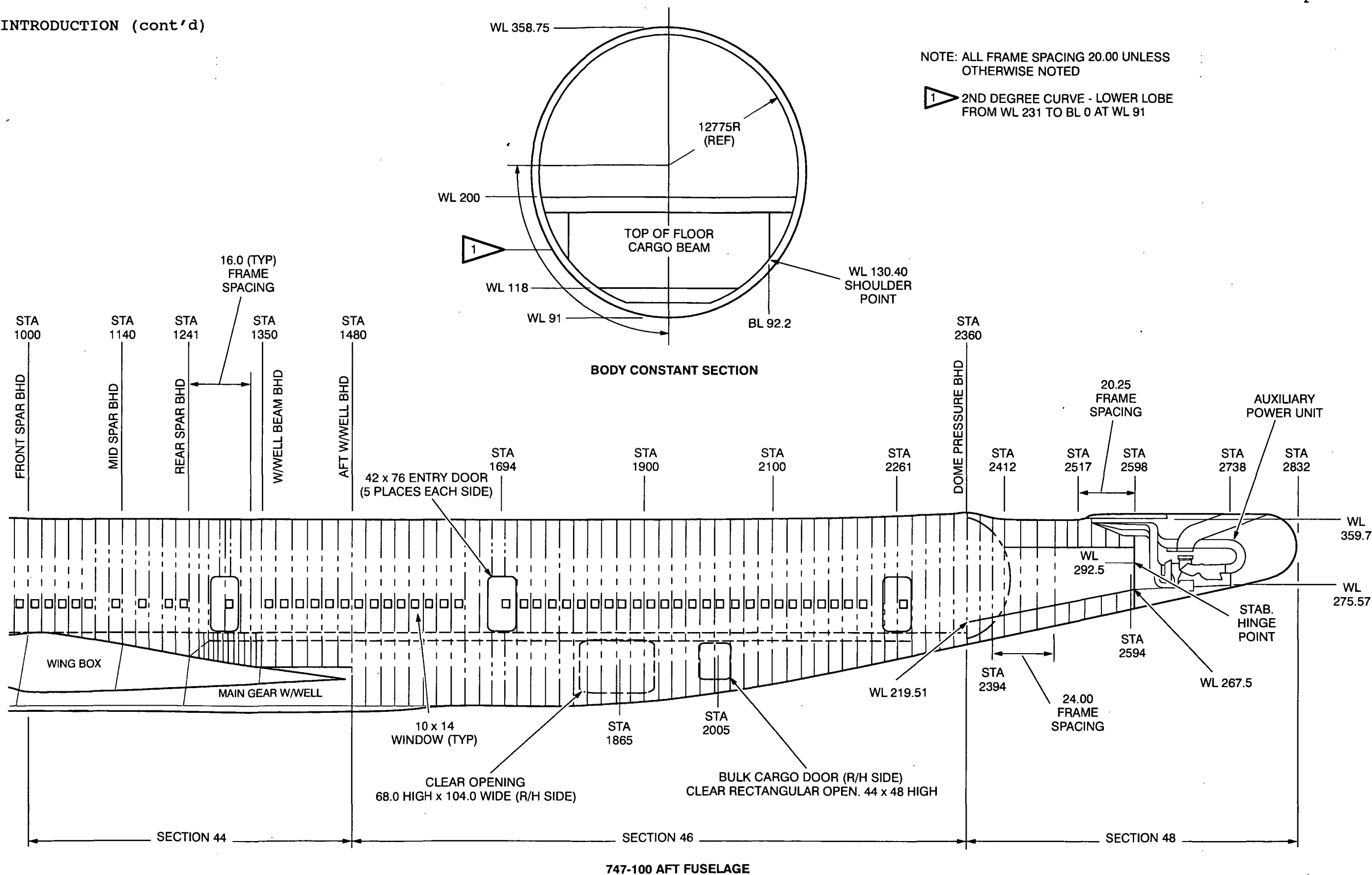
The SOFIA installation investigated in this report uses a 747-100 aircraft as its platform; this is at variance with the Phase I study which used a 747SP as the transport system (reference LAS report R3604001). This change was made to minimize cost on this limited-budget study. Lockheed had access to a previously developed model and loads which had been derived from, and FAA approved for, a 747-100 modification program. Development of loads for a 747SP SOFIA aircraft would have exceeded the available budget, even for a very simplified set of loading conditions. Also, should NASA elect to use a 747SP as the system platform, the bulk of the results contained in this report would still apply in principle; they need only be modified by the results of the detail design process as they would (although to a lesser degree) for a 747-100 platform. The basic 747-100 aft fuselage geometry is shown on page 1.2.

The fundamental SOFIA configuration is based on input from NASA and Lockheed Missiles and Space Company SOFIA Final Review LMSC/P016023. The required fuselage shell opening was defined by NASA and the Telescope mass properties were obtained from the LMSC report.

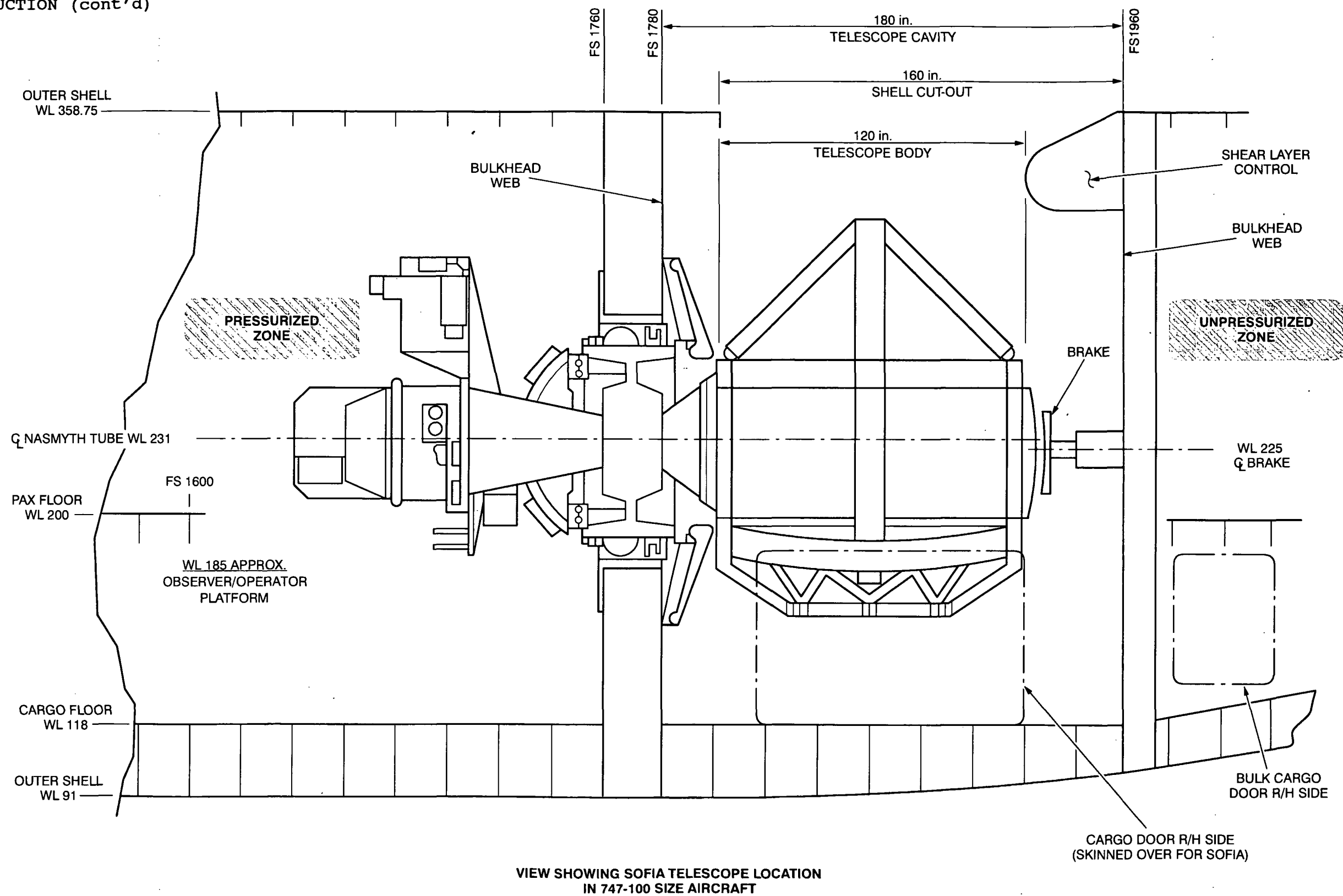
The general arrangement of the installation is shown on page 1.3. The bulkhead to bulkhead distance is 180 inches, the shell cut-out fore/aft distance is 160 inches and it is 89 degrees wide circumferentially. With these parameters the aft face of the forward bulkhead was set at FS 1780 and the forward face of the aft bulkhead at FS 1960. The center rotation of the telescope is at FS 1770, WL 231 (the origin of the upper fuselage's 117.75 inch radius) and BL 0. Between the bulkheads, the main deck floor is removed with the exception of a maintenance walkway, to permit installation of the telescope. Forward of the forward bulkhead and aft of FS 1600, the floor is cut away between BL 60 L & R to permit installation of the telescope mounting and operating mechanisms and to permit access to the instrument package.

The aircraft retains its normal pressurized cabin forward of FS 1780. The area between the bulkheads is protected from the external environment by a moveable door and orifice (NASA design), and is open to atmosphere during observation periods. The fuselage aft of the aft bulkhead is vented to atmosphere.

1.0 INTRODUCTION (cont'd)



1.0 INTRODUCTION (cont'd)



2.0 CRITERIA AND ASSUMPTIONS

The criteria and assumptions on which the SOFIA Phase II study was based are delineated in this section.

2.1 ALLOWABLE STRESS LEVELS

Several magnitudes of allowable stress levels apply to the SOFIA installation depending upon the function of the part, and upon the applied loading.

2.1.1 FATIGUE CRITICAL PARTS

The allowable stress level for fatigue critical parts are gross area tension stresses assuming a joint efficiency of 75% i.e. no more than 25% of the tension area removed by fastener installation. The stress levels are based upon Lockheed developed constant life curves for standardized aluminum.

Inspectable installations which are subject to flight loads with or without pressure loads: allowable gross area ultimate stress level is 45 ksi. As no fatigue spectrum is available to scientifically derive a value for this condition it is based upon past experience with wide-body commercial aircraft.

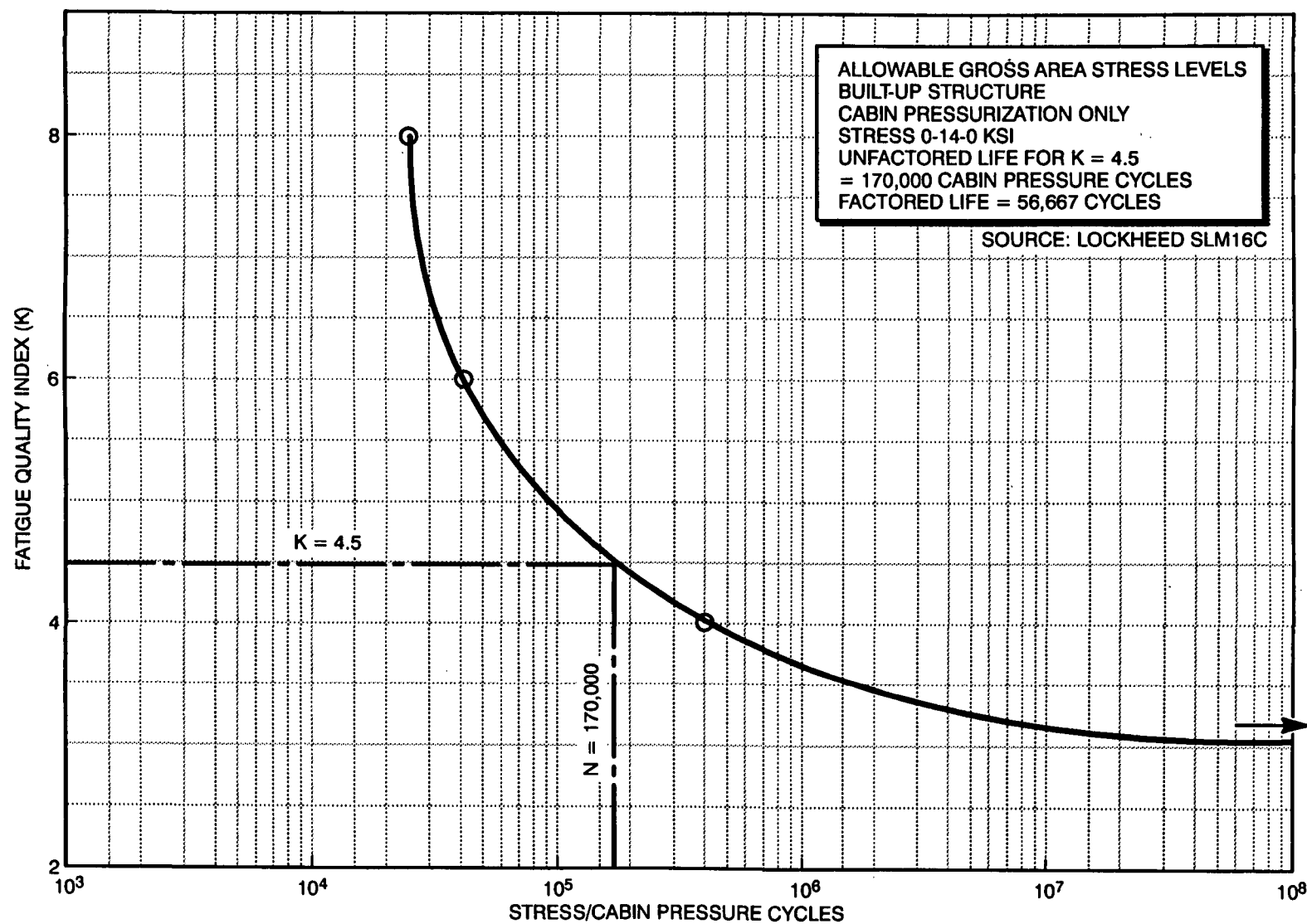
Uninspectable areas of installations which are subject to flight loads with or without pressure loads: allowable gross area ultimate stress is 30 ksi. As with the 45 ksi allowable above, this is based upon past experience.

Built-up structure subject to cabin pressurization only loads: allowable gross area tension stress is 14 ksi, limit. This allowable is based on a fatigue quality index of 4.5 and factored life of approximately 50000 cabin pressurization cycles. The allowable stress is low as it is assumed that full cabin pressurization (9.4 psi) is achieved every flight. The allowable was determined using the Constant Life Curves for standardized aluminum from the Lockheed Structural Life-Assurance Manual (SLM) and the results are shown on page 2.2.

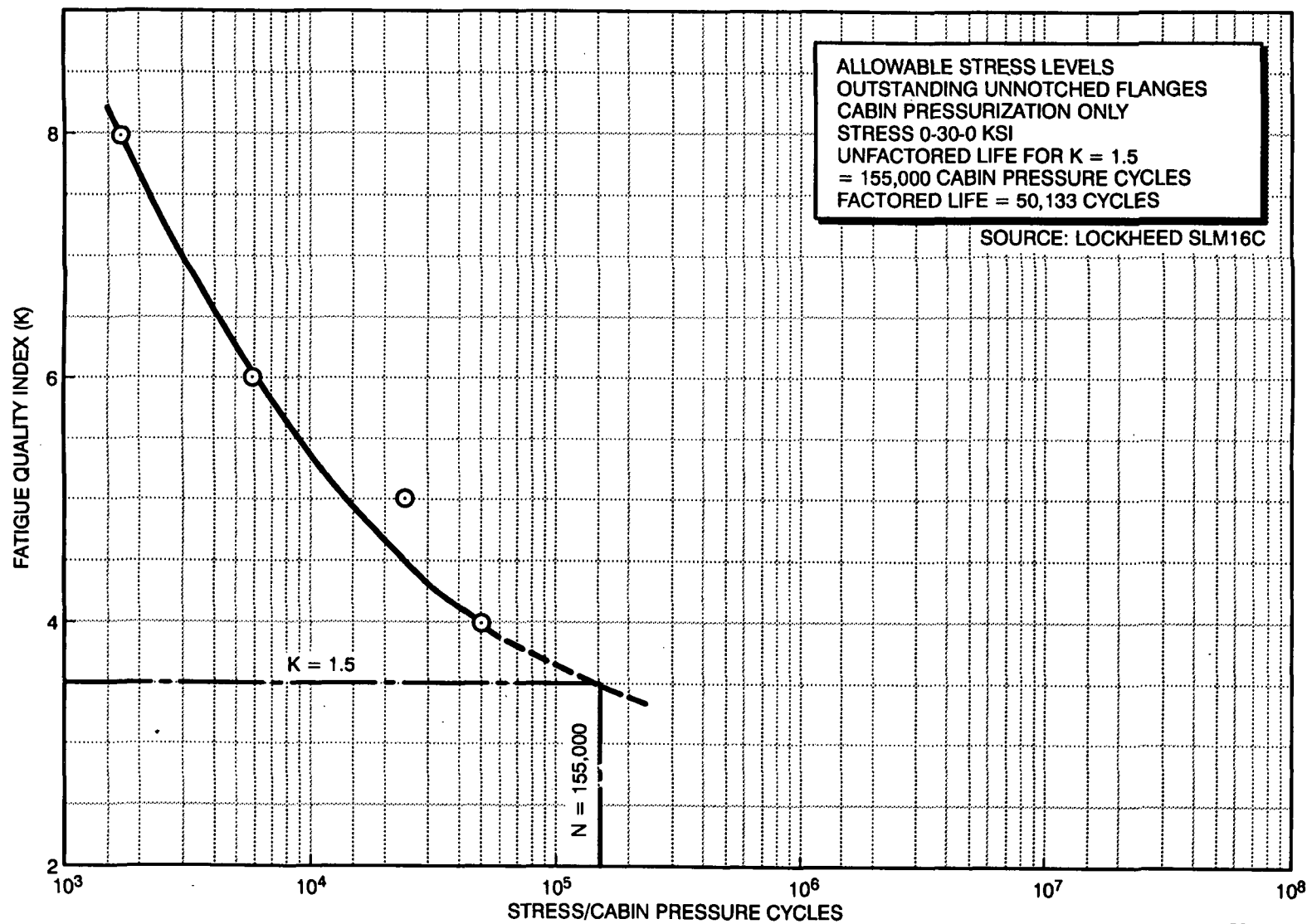
The outstanding flanges of the bulkhead pressure panels which are subject to cabin pressurization loads: allowable gross area tension stress 30 ksi, limit. This allowable is based on a fatigue quality index of 1.5 and hence, no attachments are permitted in the riser beyond the riser mid-height. This was determined from the SLM in a similar manner to the built-up structure, and the results are shown on page 2.3

2.1 ALLOWABLE STRESS LEVELS (cont'd)

2.1.1 Fatigue Critical Parts



2.1 ALLOWABLE STRESS LEVELS
2.1.1 Fatigue Critical Parts



PC005-057

2.0 CRITERIA AND ASSUMPTIONS (cont'd)

2.1 ALLOWABLE STRESS LEVELS (cont'd)

2.1.2 Non-Fatigue Critical Parts

For non-fatigue critical structure the allowable stresses are those given in MIL-HDBK-5F or other FAA approved sources. Yield allowables shall not be exceeded under limit load conditions and ultimate allowables may not be exceeded under ultimate conditions (i.e. 1.5 x limit load or Emergency Landing Conditions per FAR 25.561). Plastic bending may be used for ultimate conditions providing this does not conflict with the yield criteria at limit load.

For crash conditions the structure may suffer permanent deformation but shall not fail.

2.2 STIFFNESS REQUIREMENTS

The overall vertical and lateral bending stiffness of the SOFIA modified aircraft shall not be less than the stiffness of the unmodified aircraft. The torsional stiffness shall be as high as possible, within reason, with equivalence to the unmodified aircraft being the goal.

The forward bulkhead which supports the telescope shall deflect aft no more than 0.5 inches under limit loads at the telescope mounting points. The aft bulkhead stiffness shall be tuned to that of the forward bulkhead such as to minimize deflection effects from the pressurized to the unpressurized conditions on the telescope brake system. The brake is assumed to be actuated by a spring with hydraulic brake releases. The brake is assumed to be engaged under hydraulic failure.

2.3 MISCELLANEOUS LOAD DERIVATION AND ASSUMPTIONS

The telescope mass properties are taken from the LMSC Final Review for the telescope design (Report No. LMSC/P016023 dated 6/18/93) and are repeated here for convenience.

Telescope System Weight = 12861 kg

Telescope Inertia (kg-m²)

$$I = \begin{bmatrix} 6051 & 77 & -2595 \\ 77 & 39733 & 58 \\ -2595 & 58 & 39485 \end{bmatrix}$$

From ref 3 Preliminary FEM Report

Max Yaw Acceleration = 0.212 rad/sec²
Max Pitch Acceleration = 0.363 rad/sec²

2.0 CRITERIA AND ASSUMPTIONS (cont'd)

2.3 MISCELLANEOUS LOADS DERIVATION AND ASSUMPTIONS (cont'd)

Brake Load required to restrain telescope

As the above loads are preliminary, conservatively use a rotational acceleration of 0.5 rad/sec² for brake sizing.

Max inertia = 39733 kg-m ²	= 29205 lb-sec ² -ft
Max yawing moment	= 14602.8 lbft
Bearing to Brake Face arm	= 155 in
Load normal to brake axis	= 1130 lb
Friction coefficient	= 0.23 (assumed)
Axial brake force	= 4913 lb (limit)
	= 7370 lb (ult) - use 7500

For design study purposes the ultimate brake load is
7500 lb axial
1725 lb radial

An arbitrary 1.0 psi limit load is assumed to be acting on the aft bulkhead (1.5 psi ult)

3.0 FINITE ELEMENT MODEL

3.1 BASIC MODEL DESCRIPTION

SOFIA is modeled using the "STRAP" finite element modelling code. STRAP is a NASTRAN compatible code developed by Rasmussen and Associates, Burbank, California. The modelling was achieved by first modelling a standard 747-100 aircraft as described in the following sections.

3.1.1 GEOMETRY

The fuselage of the Boeing 747-100 aircraft aft of station 1480 is a nearly cylindrical monocoque with a modest upward sweep and contraction aft at approximately Station 1780. The Station 1480 Bulkhead is located just forward of the model, and the wheel well is located just ahead of the bulkhead. The wheel-well side lobes (left and right) and keelson attach to the bulkhead. The presence of the discontinuity in the monocoque structure, represented by the wheel well and the loads introduced by the side lobes and keelson cause a redistribution load that is noticeable up to about 300 inches aft of the bulkhead. For this reason, an adequate representation of the structure ahead of Station 1480 is necessary.

3.1.2 MONOCOQUE

The skin is supported by 51 stringers per side and the stringers are supported by frames with a 20 inch spacing throughout. Stringers 41 and 43 terminate at Frame 2120. Stringers 27 and 45 terminate at Frame 2140. Stringer 39 terminates at Frame 2160. The finite element model contains grid points at all stringers to frame connecting points. All frames and all stringers are modeled without lumping, except stringer 32A which extends (within the model) from Station 1480 to Station 1520 and is slightly offset from Stringer 33. This stringer is lumped with Stringer 33. The skin geometry is shown on Page 3.4. The stringer locations and the skin and stringer properties have been taken from Boeing data. These properties closely match those used by Boeing in the monocoque stress analysis, however, the box-beam analysis performed by Boeing will reduce the effectiveness of skin segments in compression, and will introduce compressive loads in stringers due to panels in diagonal tension. To capture these phenomena in a finite element analysis, the stiffness properties would have to be modified depending on the load condition; i.e. separate upbending, downbending, lateral bending, and pressure models would have to be used. These refinements are not required for a preliminary study and have not been implemented. Internal loads at Station 1740 for the FE model without entry doors compare reasonably well with Boeing values (see Page 3.19 and 3.20).

3.0 FINITE ELEMENT MODEL (cont'd)

3.1.3 TYPICAL FRAME

The frame dimensions follow the skin mold line as defined for the monocoque geometry. A cross section at Station 1740 is given on Page 3.5. Frames are located 20 inches apart from Station 1480 through Station 2180 at both end of the aft fuselage model. The stiffness properties of the frames are those of the representative frame at Station 1600 from Boeing data.

3.1.4 FLOORS

The aft fuselage has two floors, the main deck at WL 199.3, and the cargo deck at WL 118.0. The main deck is shown on Page 3.6 and its aft end on Page 3.7. The main deck is supported by transverse floor beams at each frame. The transverse floor beams are supported by posts (left and right) at BL 96.0. Seat tracks are located at BL 11.33, 33.99, 75.92, and 96.0, with auxiliary seat tracks at BL 67.01 and 89.67 aft of Station 2080. The seat tracks at BL 33.99 and are mounted on top of a longitudinal floor beam. This floor beam is continuous forward of Bulkhead 1480, whereas the other seat tracks are structurally interrupted at Bulkhead 1480. The cargo deck is supported directly by the inside cord of the frame, which is a deep beam between BL 60L and 60R. The cargo deck slopes up at the forward end of the bulk cargo compartment (aft of Station 1920). (Reference Page 3.8)

3.1.5 ENTRY DOORS

The aft fuselage model contains the entry doors (left and right) between Frame 1660 and 1720 and the C1 Lower Hold Cargo Door between Frame 1800 and Frame 1920 on the right hand side. The lower Hold Bulk Cargo Door aft of Station 1980 on the right hand side has been omitted. Entry doors have been omitted and openings have been modeled as "skinned over" with the original skin, stringer, and frame properties. The surround structure of each entry door consists of upper main, upper auxiliary, lower main and lower auxiliary skills, frame reinforcements, and skin gage increases. Properties have been obtained from Boeing data. (Reference Page 3.9 & 3.10)

3.1.6 SUBSTRUCTURE FORWARD OF STATION 1480

The fuselage and wing forward of Station 1480 has been modeled as a substructure (or super-element). This substructure represents the Station 1480 Bulkhead, the stub wings and the fuselage center section in the analysis of the aft fuselage. The general lay-out of the FE model ahead of Station 1480 is shown in this report.

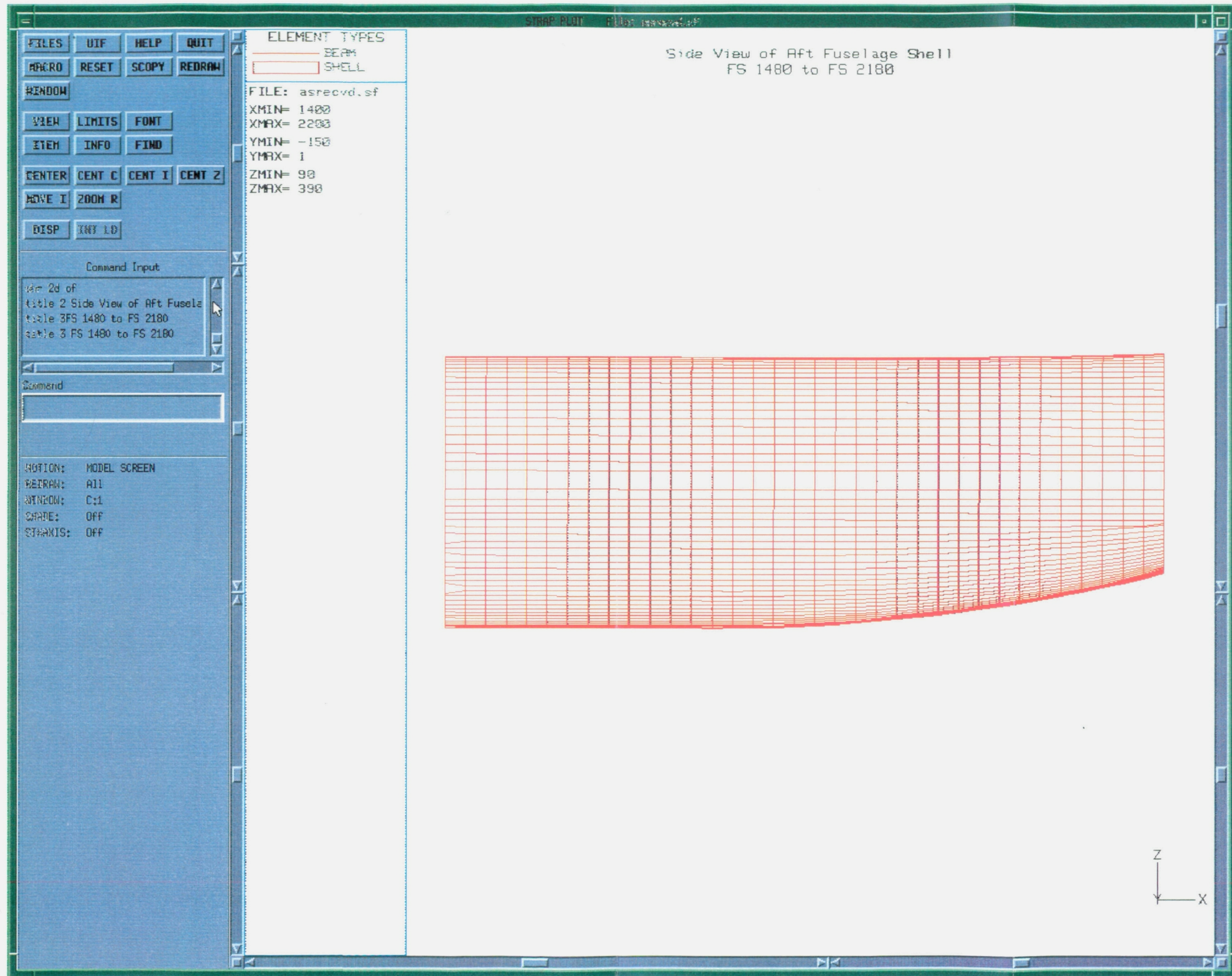
3.0 FINITE ELEMENT MODEL (cont'd)

3.1.6 SUBSTRUCTURE FORWARD OF STATION 1480 (cont'd)

The substructure has been derived from a Boeing 747 wing to fuselage intersection model. The accuracy of this model is not guaranteed for the individual stiffness elements. However, the overall stiffness properties of this model are believed to be sufficiently accurate for the purpose of constraining the current aft fuselage model at Bulkhead 1480 by means of the constraint points provided in the forward fuselage and at the stub-wing tips. A view of the model is shown on Page 3.11.

The baseline model from which SOFIA was developed is shown pictorially on the following pages as listed on the chart below:

PAGE	DESCRIPTION
3.4	Side view of Fuselage Shell FS1480 to 2180
3.5	Cross section of a Typical fuselage frame (FS1740)
3.6	Top view of main deck floor (FS2040 to FS2180)
3.7	General view of main deck floor (right hand side) FS1480 to FS2180
3.8	General view of cargo floor (right hand side) FS1480 to FS2180
3.9	Skinned over cargo door and framing reinforcement
3.10	Skinned over passenger entry door and framing reinforcement
3.11	General view of sub-structure forward of FS1480



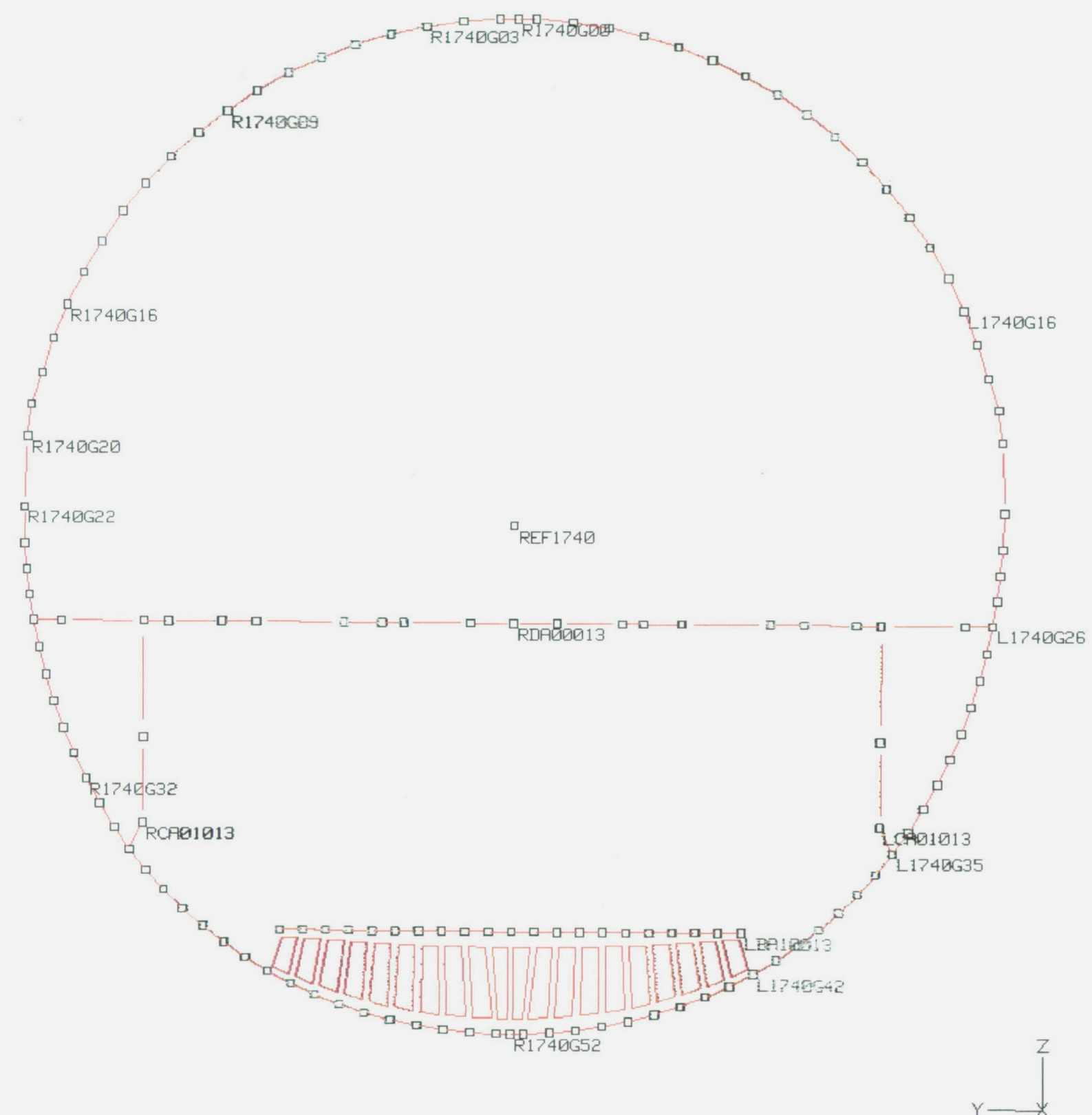
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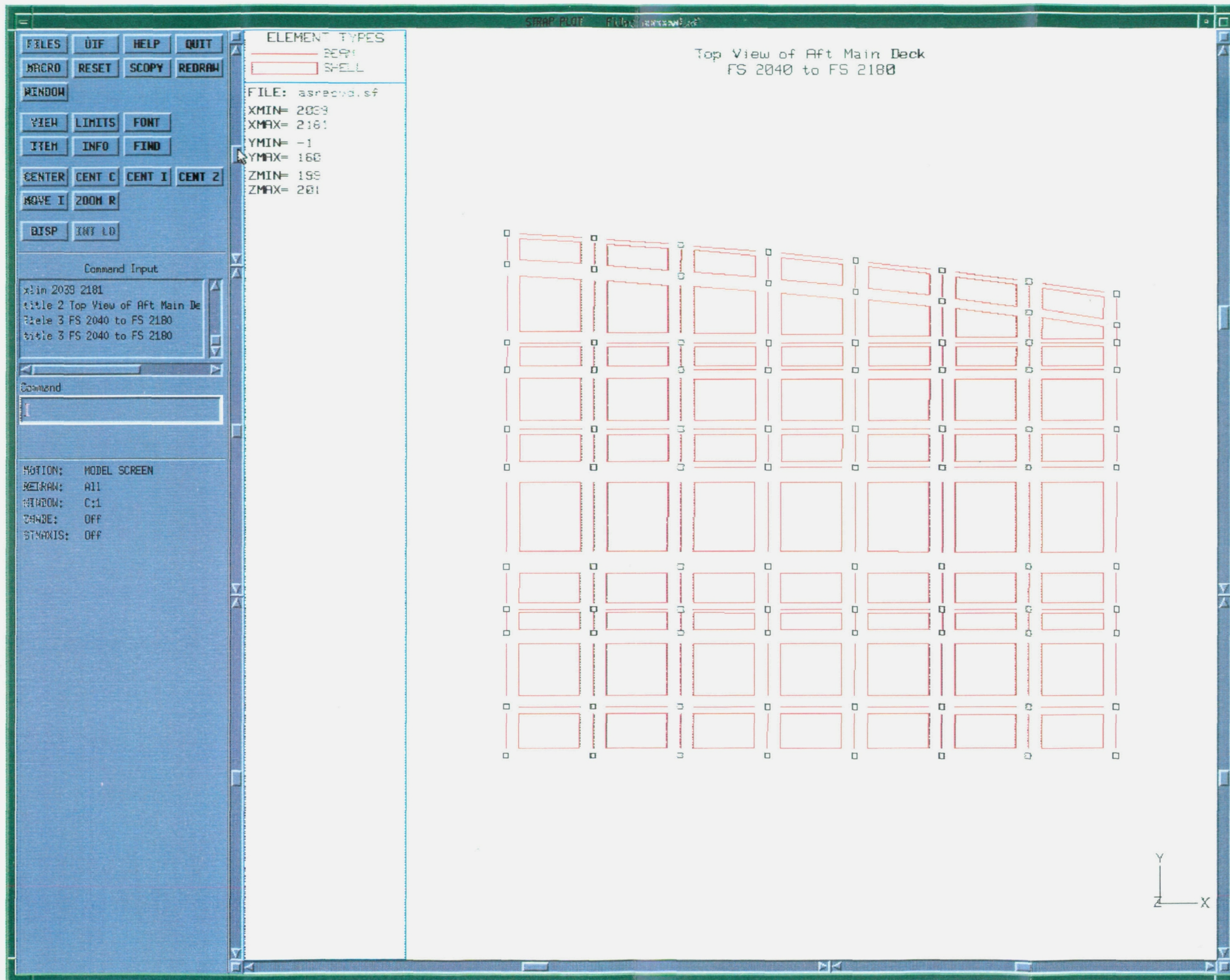
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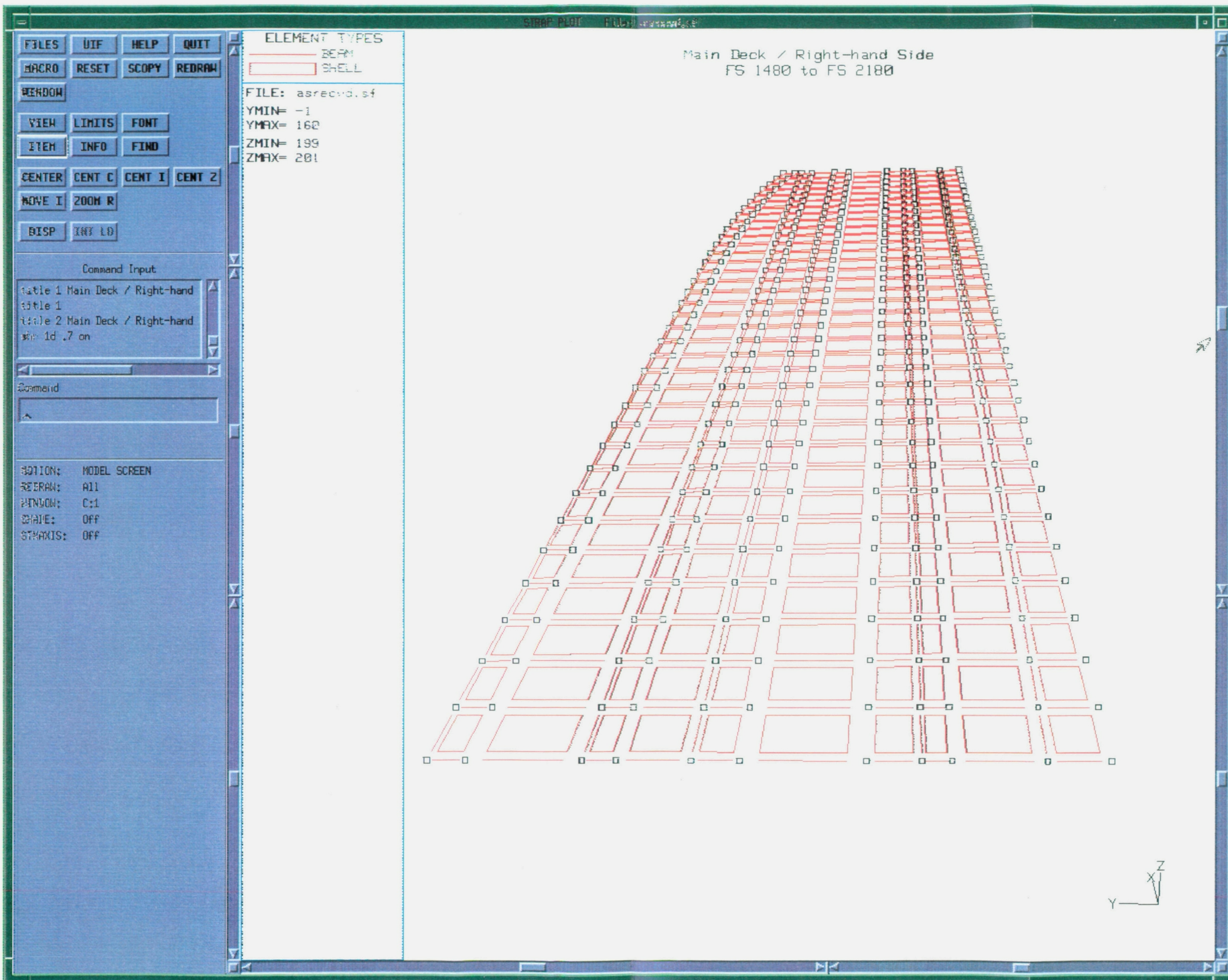
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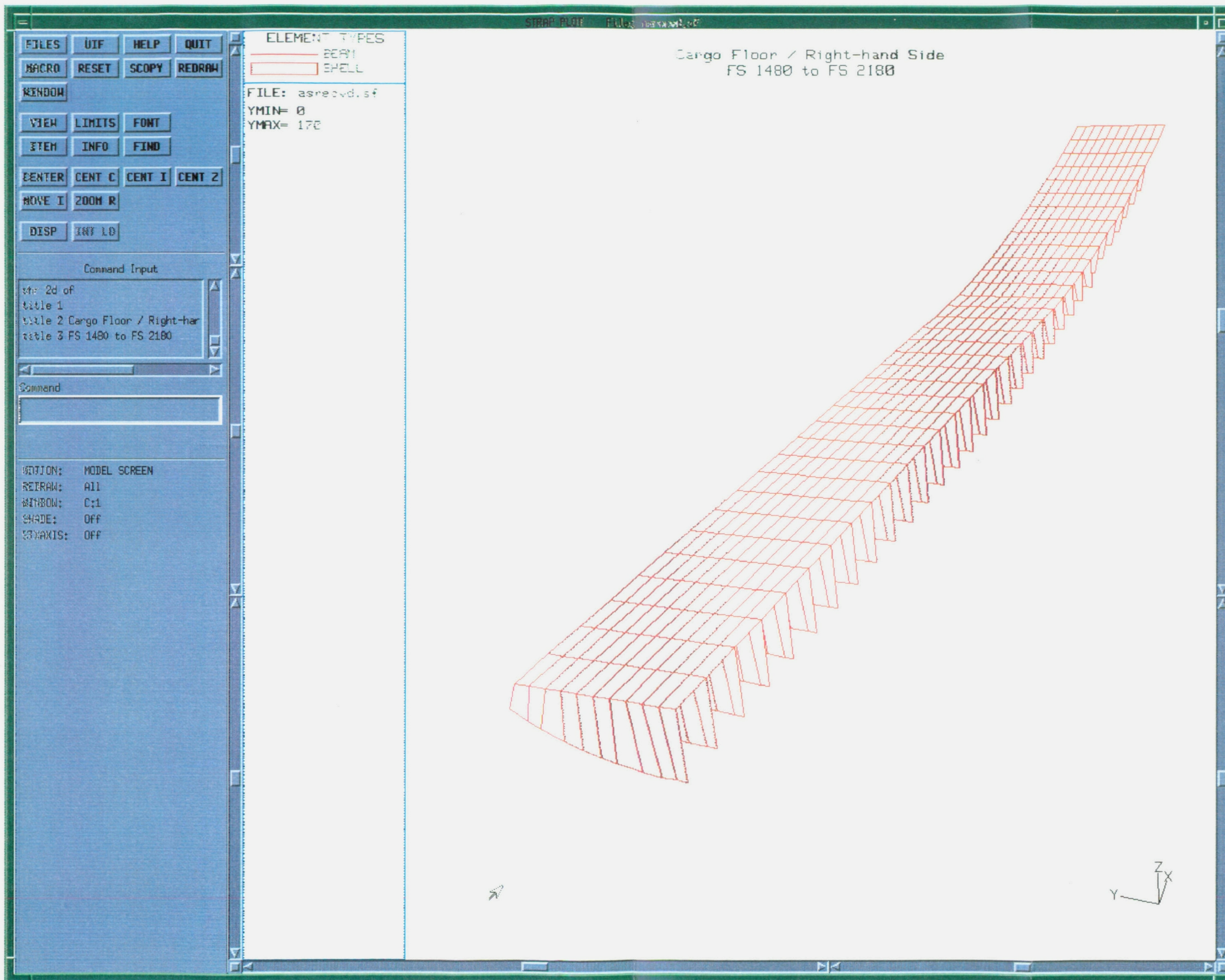
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 BEAM
 SHELL
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 ZMAX= 390

FS 1740 Cross Section







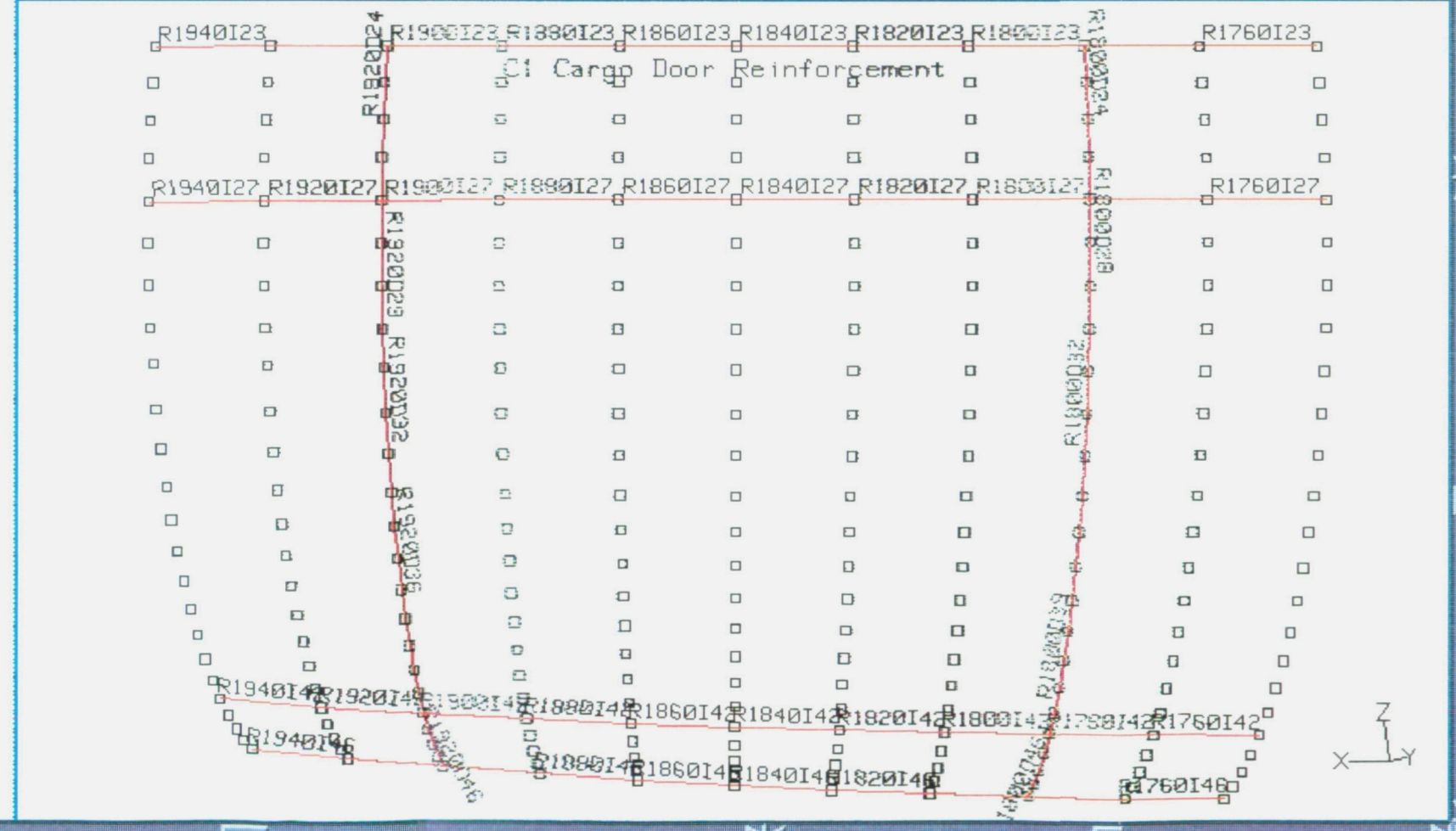
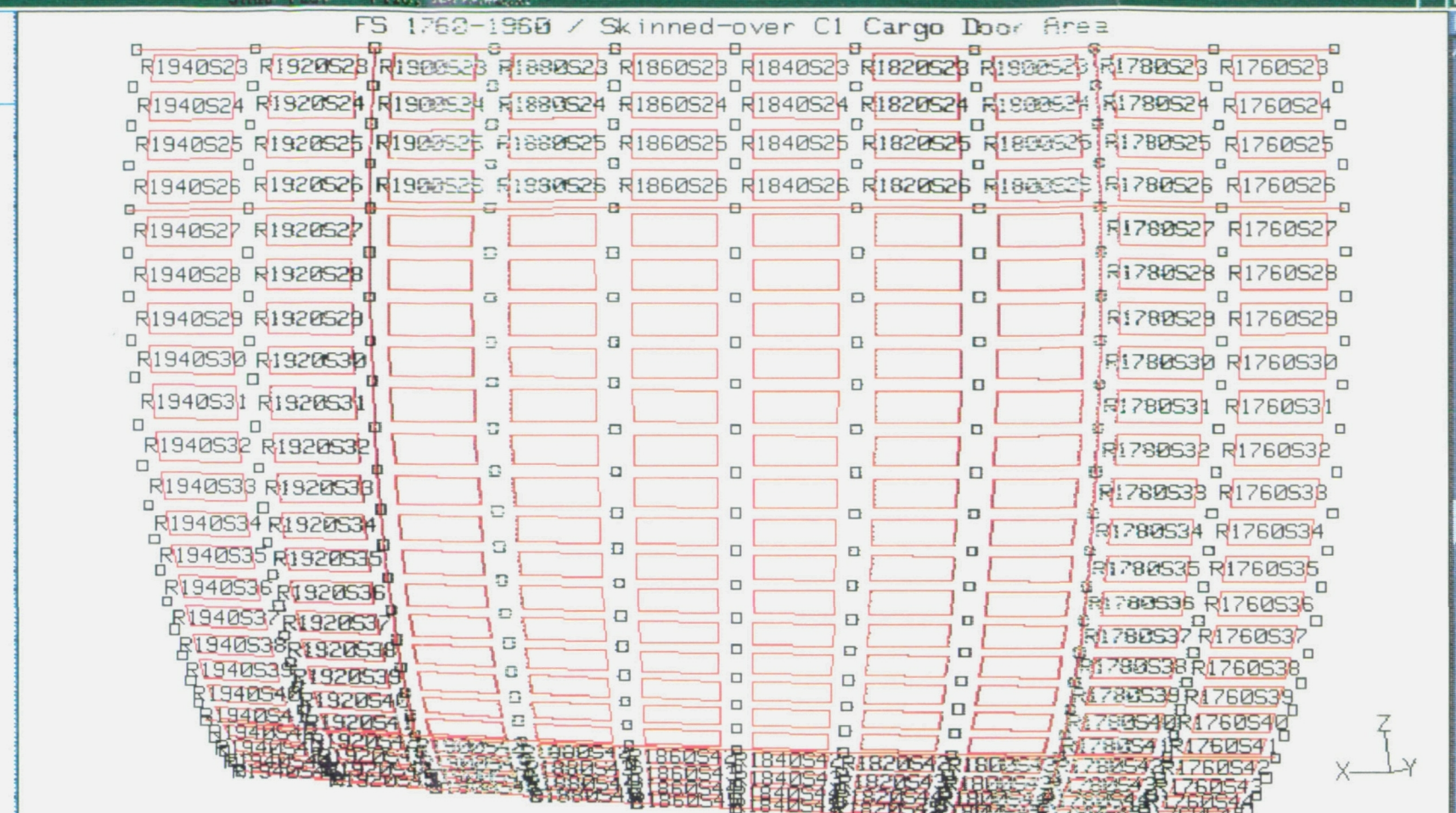


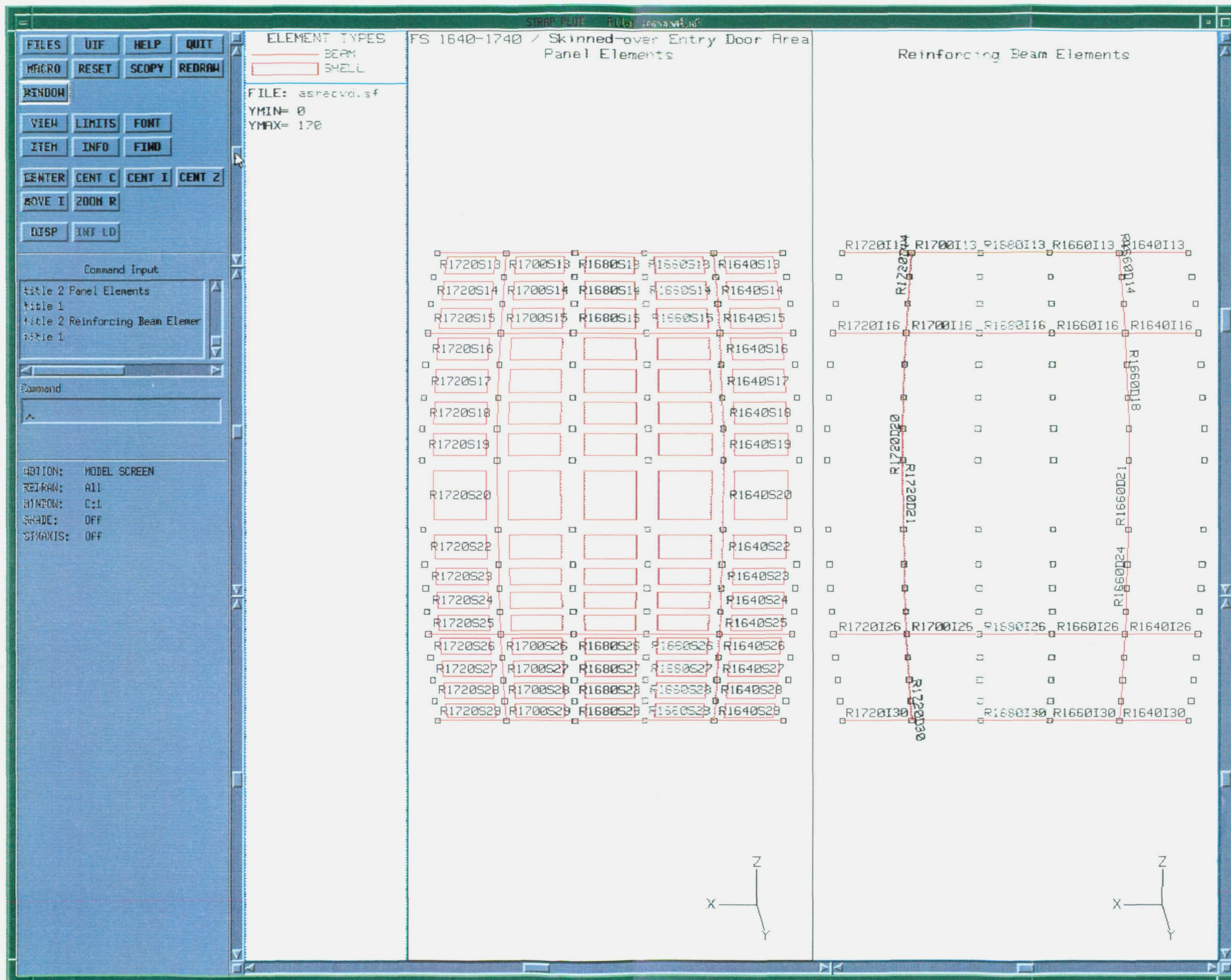
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 CENTER CENT C CENT I CENT Z
 MOVE I ZOOM R
 DISP INT LO

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 color shell black
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 title 2
 Command
 1

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RIGID
SHELL

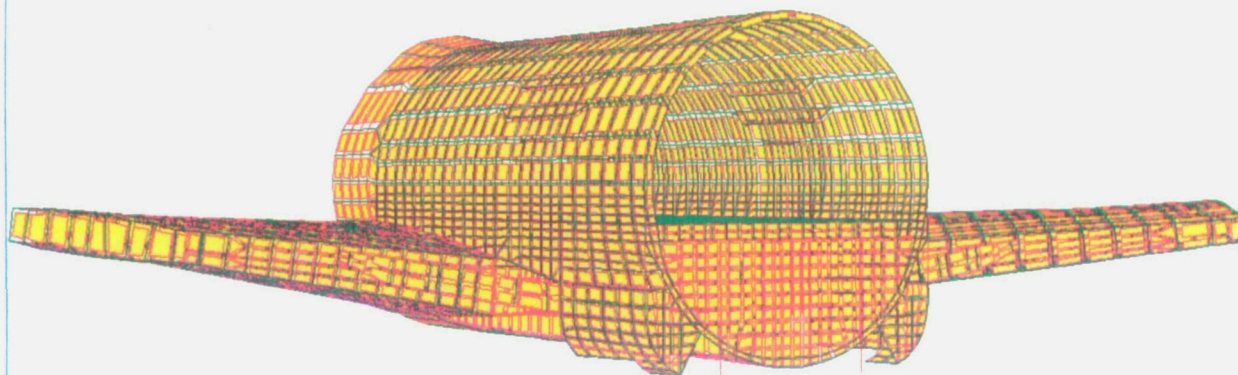
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SOFIA FINITE ELEMENT MODELING

Boeing 747 Center Section Substructure

FS 900 -- FS 1480 Including Stub Wings

3.0 FINITE ELEMENT MODEL (cont'd)



Page 3.11
Model 747
Report R54045007

3.0 FINITE ELEMENT MODEL (cont'd)

3.2.0 LOADS

Preliminary design loads for the aft fuselage model have been developed from envelope loads in Boeing data. The shear moment and torque distribution of the load cases applied to the model are shown on Pages 3.17 and 3.18.

3.2.1 LOAD CASE SELECTION

Three basic load cases have been developed; a vertical down bending envelope case, a pure lateral bending envelope case, and a pressure case for pressure relief valve pressure difference of 9.4 psi. The bending envelope cases have shears and moments introduced at each frame station of the model to match the envelopes from Boeing data in both shear and moment just aft of each frame. The three basic load cases are combined into five additional load cases. First, the vertical load case is scaled to obtain an approximate 1.5-g vertical load distribution, representing level flight. The scaling factor is $1.5/3.75$, because the vertical load envelope is determined by maneuver conditions having a 3.75 load factor over most of the aft fuselage length. The scaled vertical bending envelope is combined with the lateral load case to obtain the fourth load case; lateral load combined with level-flight. A fifth load case is obtained by scaling the pressure conditions to 2.0 factored pressure. The three remaining conditions are obtained by combining 1.5 factored pressure with the two lateral and the vertical bending cases.

Condition	Description
Vertical	Downbending Envelope
Lateral	Lateral Bending Envelope
IP	9.4 Psi Cabin Pressure (P)
1g FLT	1.5g Level Flight
LateNzo	1.5g Level Flight & Lateral Bending
2P	18.8 Psi Cabin Pressure
Vertical + P	1.5P + Downbending Envelope
Lateral + P	1.5P + 1.5g Level Flight & Lateral Bending
LateNzo + P	1.5P + Lateral Bending

3.0 FINITE ELEMENT MODEL (cont'd)

3.2.1 LOAD CASE SELECTION (cont'd)

Internal loads at Station 1740 are compared to Boeing Box Beam analysis results on Page 3.18 and 3.19 for the vertical envelope condition "Vertical" and the lateral envelope conditions "Lateral" and "LateNzo", representing lateral loads with and without vertical loads, respectively. The internal loads for the Vertical Condition show a fairly good match, both in shear flow and in longitudinal stress, except that longitudinal stress exceeds Boeing values in the top (in tension) and is somewhat less in the bottom (in compression) of the monocoque. These differences are considered a result of differences between Box Beam and FE analyses, as mentioned in Section 3.1.1. The Boeing lateral condition is bracketed in shear between the lateral conditions with and without 1-g vertical loads. The longitudinal stress for the lateral condition with vertical shear is slightly exceeded by the stress for the Boeing condition (in compression) around Stringer No. 30. The Boeing box beam analysis is simply a unit beam solution with adjustments made to accommodate cutout effects.

3.2.2 LOAD CASE APPLICATION TO MODEL

The incremental shears, bending moments, and torsion are applied to reference points at each frame in the plane of symmetry at W.L. 225. These points are connected to the fuselage monocoque structure using a splining element (RSPLINE) that introduces the loads without modifying the stiffness of the model. This element employs a factored least-squares technique to distribute loads into each frame. Shears are distributed uniformly in pounds/inch over the circumference, and moments are distributed as a linear pounds/inch distribution about a neutral axis. Torsion is introduced as a nearly uniform $T/2A$ shear flow. Most of the incremental loads introduced at the frames consist of inertia loads, as airloads on the fuselage are relatively small. Therefore, the true application pattern of the inertia loads is less smooth than the one employed here. In both cases, smooth or discrete, the stiffness properties of the frame and adjacent skin cause the applied incremental loads to be redistributed in accordance with the compliance of the structure within a frame spacing length. In the Boeing box beam analysis, incremental loads are also applied in a smooth distribution.

For variations of the current model, the splining can easily be modified by removing or adding load points in the definition. The distribution of load can be influenced by changing factors. For example, large masses, such as the SOFIA telescope, can be represented by interior points with a relatively high factor (to attract load).

3.0 FINITE ELEMENT MODEL (cont'd)

3.2.2 LOAD CASE APPLICATION TO MODEL (cont'd)

The benefit of the splining method is that load can be distributed into complex models with little effort. However, an acceptable load distribution for (preliminary) design can only be obtained with a sufficient number of points, distributed vertically and horizontally over the frame. A point set without vertical spread, for example, cannot be used to introduce vertical bending. The load distribution that is created can be examined using grid point force analysis.

Pressure loads are applied to the model using a distributed pressure over each panel. At the model ends, loads are distributed to triangular areas: two support points along the edge of the monocoque, and the third point a centrally located reference point. The sum of the load applied to the reference point is transferred back to the edge using the splining method described above. Again, the total pressure load is area-integrated in the finite element calculation. Subsequently, this load is distributed in a uniform manner over the edge of the monocoque by the spline. At the forward end, pressure loads are applied at the wheel-well pressure bulkhead only. The balance of the pressure load, equal to the pressure times the open area above the wheel well at Station 1480, is reacted by the substructure forward of that station.

3.2.3 AFT FUSELAGE ACCELERATION

Critical SOFIA design vertical and lateral accelerations are obtained for light-weight gust conditions and a two-wheel level landing condition. The actual SOFIA A/C weight and c.g. location have not yet been determined. Therefore, an Operating Empty Weight (OEW) of 327,000 lbs. at 34.9% from Boeing data has been incremented by 33,000 lbs. of weight in the forward fuselage to bring the c.g. to the forward limit of 14% MAC. Yaw and pitch inertia have been estimated based on the length of the fuselage, the OEW and the fuel and payload weights are listed on Page 3.15. Actual SOFIA weights will be higher than those in the table and will have a more aft c.g. due to the telescope installation weight that is added to the aft fuselage.

Therefore, actual accelerations will be less than those calculated in this report. Accelerations are documented on page 3.15. The gust accelerations have been calculated using FAR 25.341(b)3 and 25.1351(b) for gust at V_c and the aerodynamic derivatives from the table on Page 3.16.

3.0 FINITE ELEMENT MODEL (cont'd)
3.2.3 AFT FUSELAGE ACCELERATION (cont'd)

747-100 Weight Conditions

Cond.	GW kips	c.g. MAC	IYY in-lb-sec ²	Izz in-lb-sec ²
000	327	34.9%	.258E+09	.374E+09
001	360	13.0%	.305E+09	.422E+09
002	585	13.0	.480E+09	.611E+09

747-100 LIMIT Acceleration Design Conditions

(NY, $\ddot{\Psi}$ apply to Lateral Gust, Nz, $\ddot{u}$ to others,
Gust Conditions at Vc; 375 KEAS at 20kFT, or M 0.92 at
40 kFT)

Cond.	Type	GW	c.g.	Alt.	Ny/Nz	$\ddot{u}/\ddot{\Psi}$
		kips	%MAC	KFT	LIMIT	rad/sec ²
GL01.1	Lat. Gust	360	0.13	20	0.51	0.212
GL02.1	Lat. Gust	360	0.13	40	0.24	0.100
GN01.1	-Gust	360	0.13	20	-1.02	0.363
GN02.1	-Gust	360	0.13	40	-0.16	0.201
GP01.1	+Gust	360	0.13	20	3.02	-0.363
GP02.1	+Gust	360	0.13	40	2.16	-0.201
LL01.2	2WLL	585	0.13	S.L.	2.15	-0.190

2 WLL Two-wheel Level Landing at Maximum Vertical
Reaction

3.0 FINITE ELEMENT MODEL (cont'd)

3.2.3 AFT FUSELAGE ACCELERATION (cont'd)

747-100 Geometric Data

Mean Aerodynamic Chord	MAC	327.8 in
Leading Edge of MAC	LEMAC	1258 in
Wing Reference Area	S	5500 ft-sq
Wing Span	B	2348 in
Length of Fuselage	LFUS	2702 in
Fuselage Station of Horizontal Stabilizer 25% MAC	Xtail	2495 in
Distance from 25% Wing MAC to 25% Horizontal Stabilizer MAC	Ltail	1254.05 in
Horizontal Stabilizer Reference Area	Sht	1470.7 ft-sq
Wing Aspect Ratio	A	6.96
Horizontal Stabilizer Aspect Ratio	Aht	3.6

3.0 FINITE ELEMENT MODEL (cont'd)

3.2.3 AFT FUSELAGE ACCELERATION (cont'd)

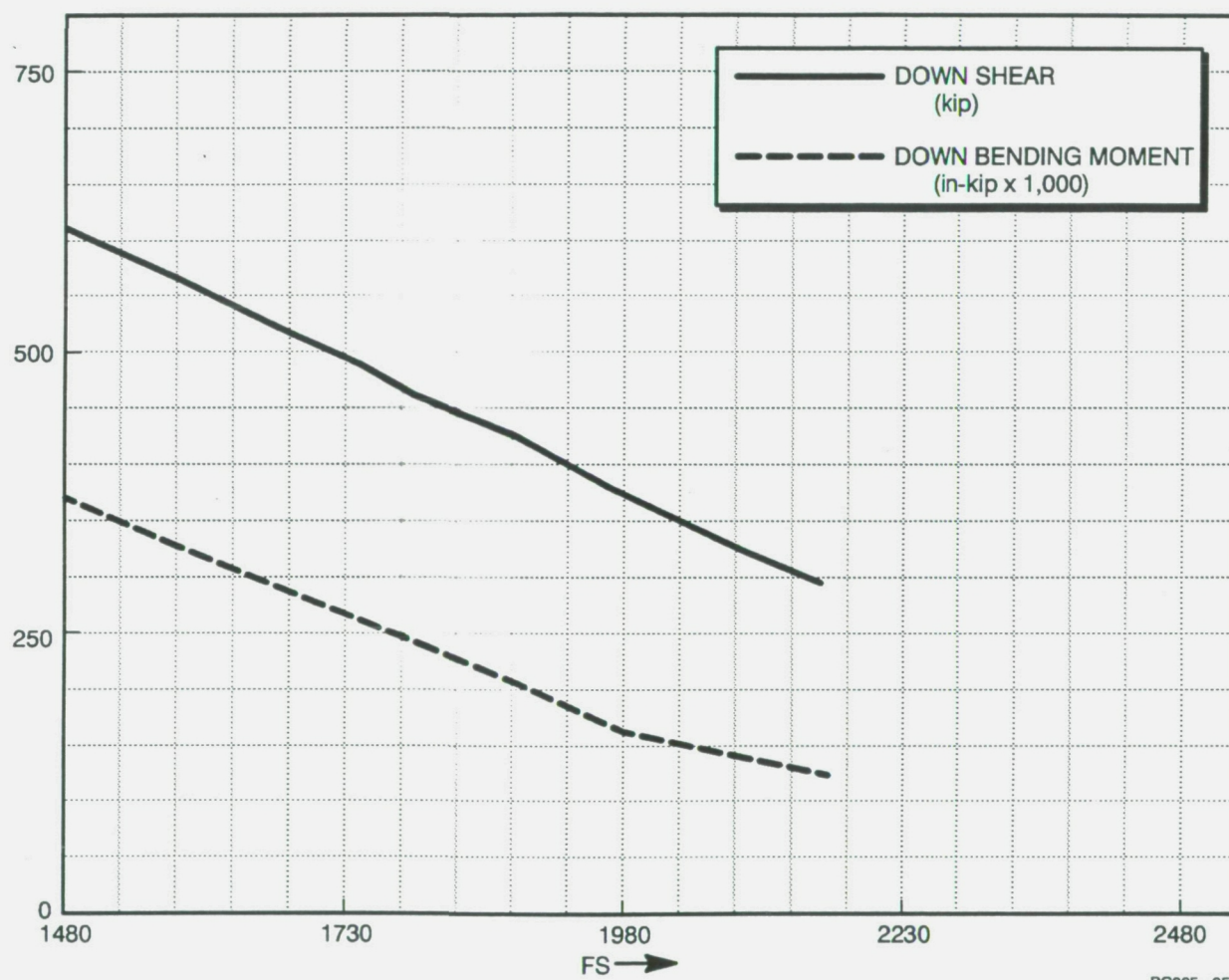
747-100 Aerodynamic Derivatives

Altitude	Alt. (kft)	20	40
Velocity	Ve (keas)	375	262
Mach Number	M	0.836	0.92
Lift Derivative Tail Off	CL alpha (1/deg)	0.0736	0.0855
Pitching Moment Derivative Tail Off	Cm alpha (1/deg)	0.0150	0.0084
Rate of Change of Down Wash with (respect to alpha)	deda	0.3857	0.4481
Lift Derivative Tail On	CL alpha (1/deg)	0.0852	0.0959
Pitching Moment Derivative - Tail On	CM alpha (1/deg)	0.0293	-0.0314
Side Force Derivative	CYbeta (1/rad)	-1.0258	-1.0258
Directional Stability (Weather Cocking Derivative)	Cnbeta (1/rad)	0.1964	0.1964

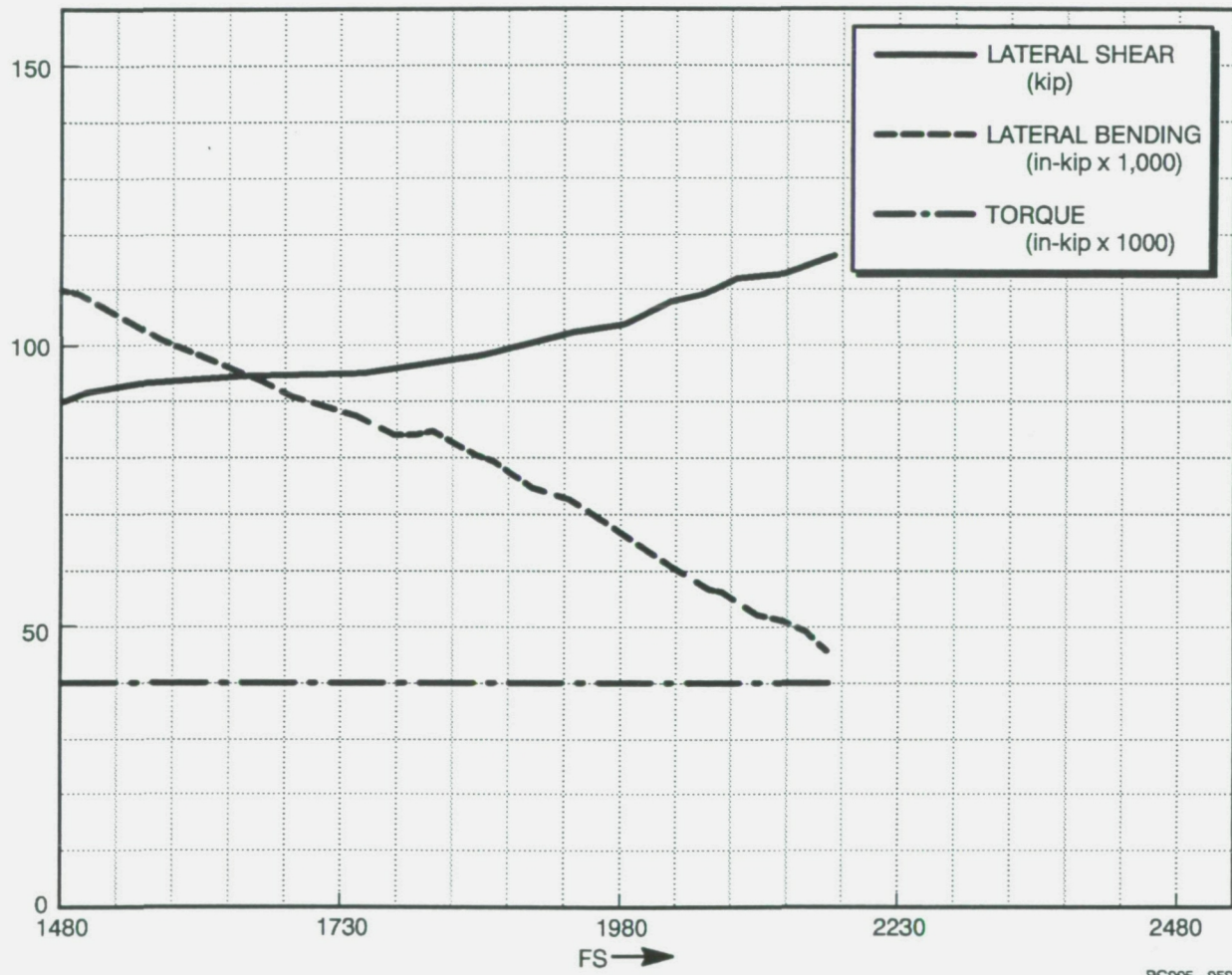
Where ALPHA is angle of attack
BETA is angle of yaw

Acceleration Due to Gravity g 32.2 ft/sec-sq.

3.0 FINITE ELEMENT MODEL (cont'd)
3.3 ENVELOPE LOADS
3.3.1 Aft Fuselage Vertical Envelope Loads



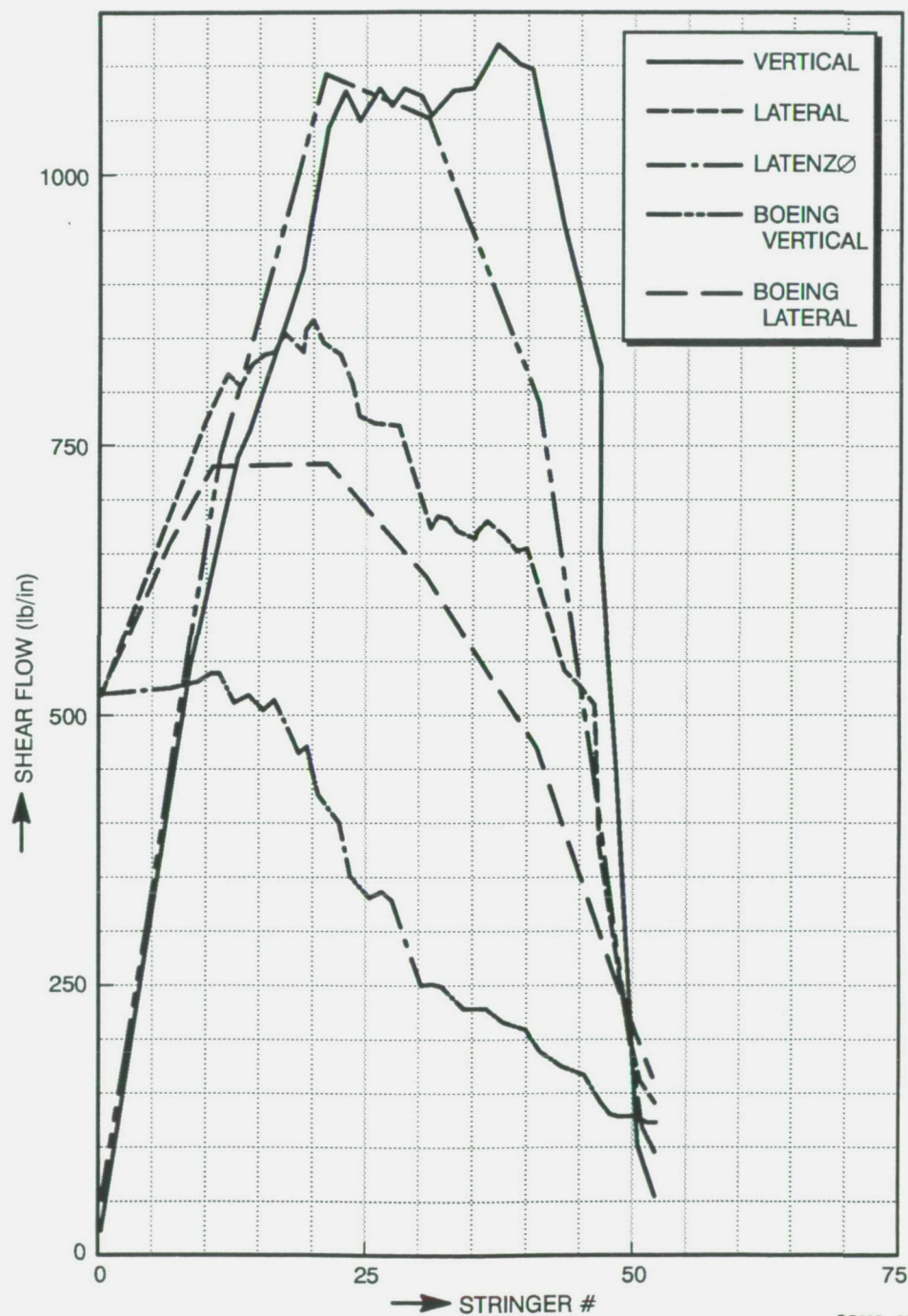
3.0 FINITE ELEMENT MODEL (cont'd)
3.3 ENVELOPE LOADS (cont'd)
3.3.1 Aft Fuselage Lateral Envelope Loads



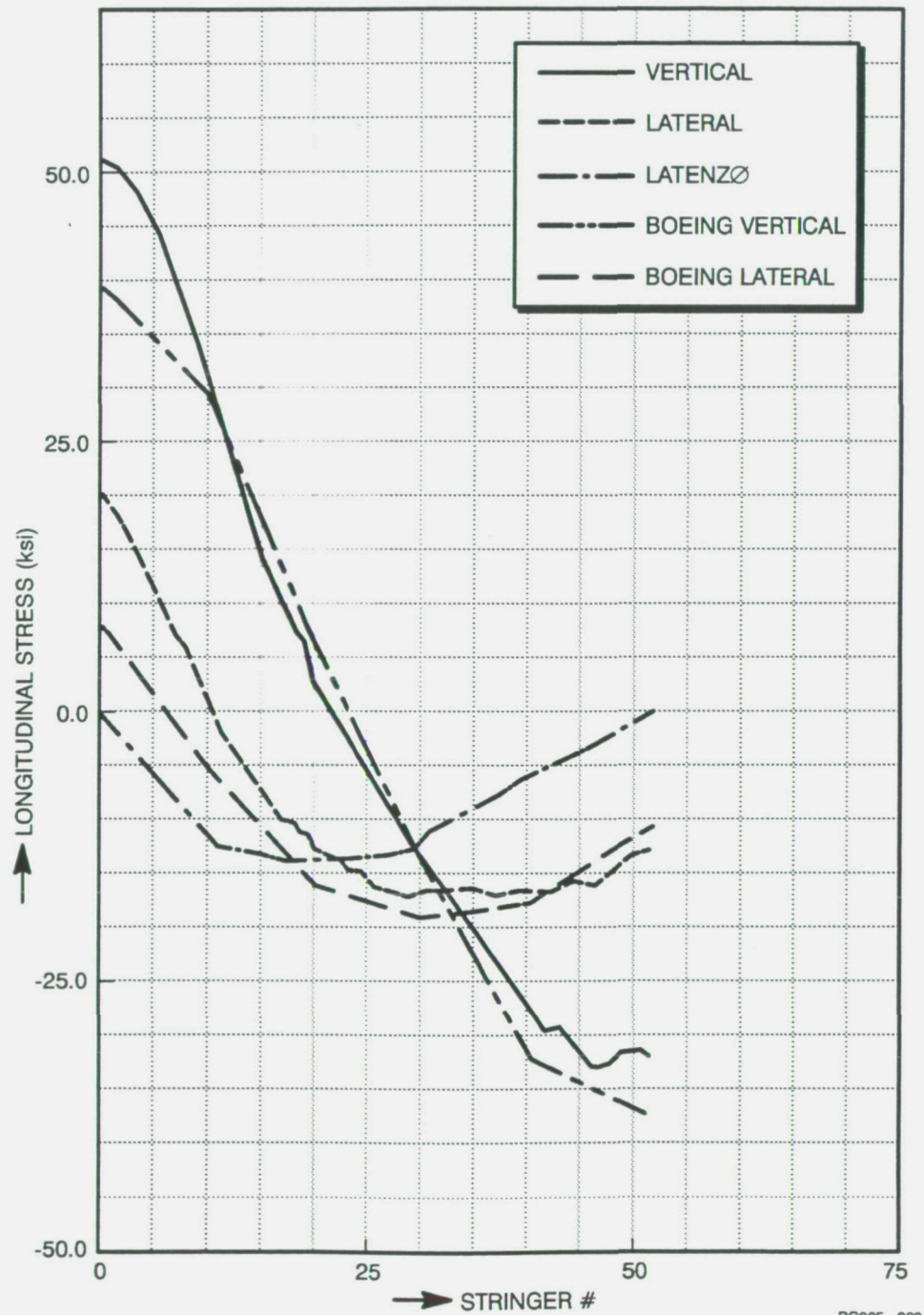
3.0 FINITE ELEMENT MODEL (cont'd)

3.4 OUTPUT COMPARISON

3.4.1 Shear Flow Comparison - Aft Fuselage without Doors FS 1740



3.0 FINITE ELEMENT MODEL (cont'd)
3.4 OUTPUT COMPARISON (cont'd)
3.4.1 Longitudinal Stress Comparison - Aft fuselage without Doors
FS 1740



3.0 FINITE ELEMENT MODEL (cont'd)
3.5 SOFIA MODEL

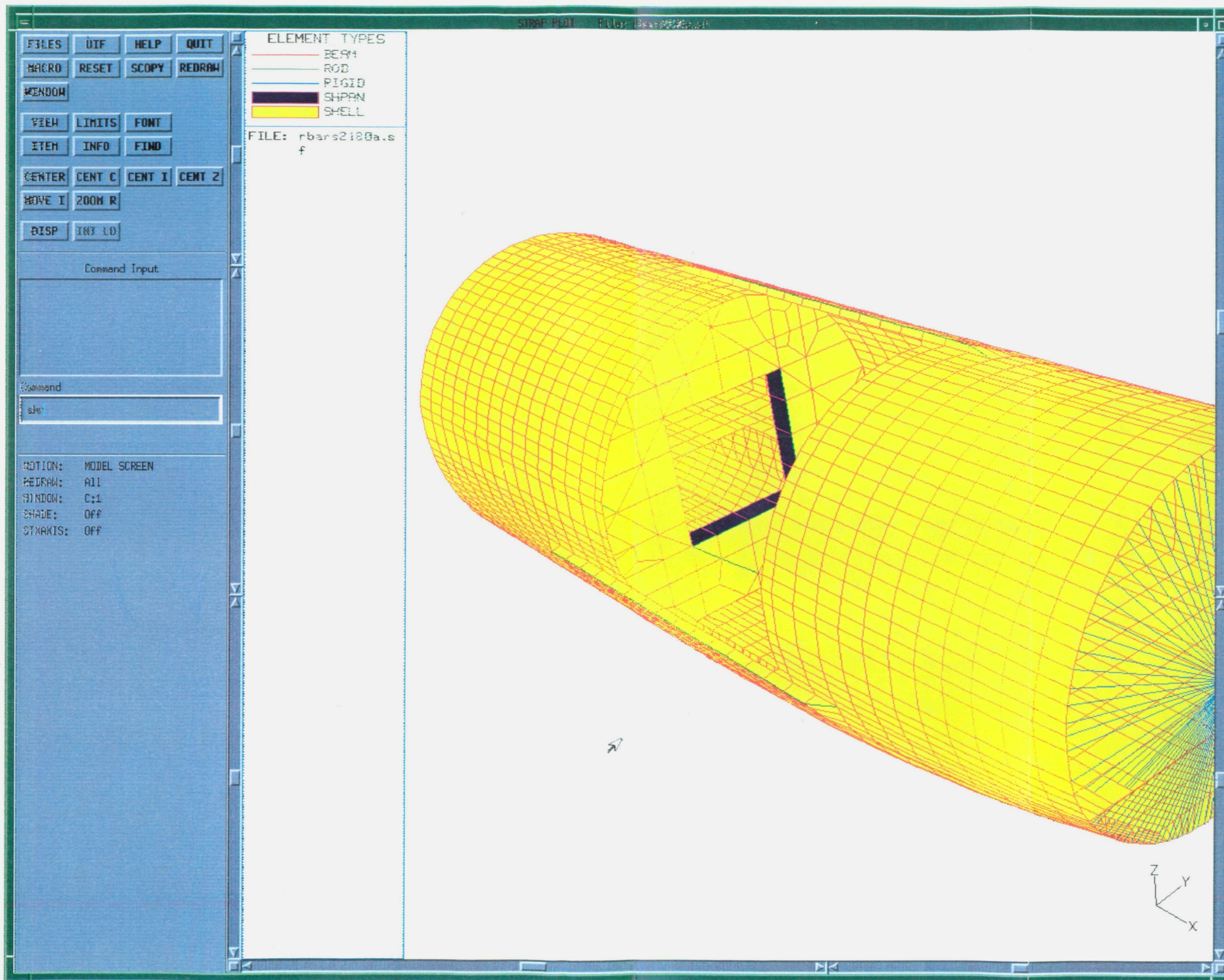
The basic 747-100 Finite Element Model described in the preceding sections was modified to reflect the SOFIA configuration.

The stringers were eliminated at the shell cutout and the skin panel thicknesses increased to reflect the surround doublers. The stringer elements in the area of the primary and secondary longerons were increased in area and moment of inertia and also had offsets incorporated to simulate the longeron centroid shifts. In the initial modeling the longerons were discretely modeled with individual elements for caps, webs, etc., but with evolving designs this was found to be too time consuming considering the budgetary constraints, and so the lumped approach was taken.

The forward bulkhead was discretely modeled throughout the study as it was felt to be important that the loads at the bulkhead to shell transition be understood. The transition intercostal was modeled down to the fastener level at one location while at all other locations they were incorporated as beam elements only. The discretely modeled intercostal was run for the 9.4 psi condition only, as this is the condition on which the life estimate is based.

The aft bulkhead was modeled using beam elements for the bulkhead beams as opposed to discretely modeled elements.

The aft fuselage model is shown on page 3.23.



4.0 STRUCTURAL DESCRIPTION AND ANALYSIS RESULTS

4.1 FORWARD BULKHEAD

The forward cavity bulkhead is centered at FS 1770 and performs three major functions:

- i) It forms the aft boundary of the pressurized portion of the fuselage.
- ii) It supports the mass of the telescope and associated equipment.
- iii) It acts as the primary forward framing member for the observation cut-out.

The bulkhead and support beams are shown on sheets 2, 3, 4, & 8 of Drawing B54114000.

The bulkhead is a flat pressure web supported by 20 inch deep beams with the web located at FS 1780 and the support beams extending forward to FS 1760. The bulkhead contains a 100 x 100 inch cut-out to accommodate the telescope support bearing and pressure seal.

The pressure web is fabricated from 20 inch wide extruded panels with a maximum length of 20 inches between supports. These panels have 0.94 inch high bulb risers at approx 1.5 inch O/C (Lockheed extrusion no. LS5150). The risers face aft into the cavity and are locally machined away to accommodate the cap splice plates and pressure plenum. The basic LS5150 extruded panel is 7075-T6 but as this design will have extensive machining to accommodate the splice plates and plenum seal, the extrusion should be in the T73 over-aged condition to minimize exfoliation and stress corrosion problems.

The main beams are 20 inches deep and are of conventional cap, web, and stiffener construction. As the bulkhead is stiffness critical the shear web is designed to be non-buckling under normal operating conditions. This results in the shear webs outside the circle inscribed by the pressure plenum seal being 0.08 inch thick and those inside the circle being 0.063 thick. In addition, where the bulkhead to shell transition intercostals occur, the webs are locally doubled up to present a flat surface to the transition cap members. The caps are extruded "Tee" sections tapering in thickness toward the shell. The caps are spliced at the joints using external plates and internal bathtub fittings and bolts. This is true for both the forward and aft caps.

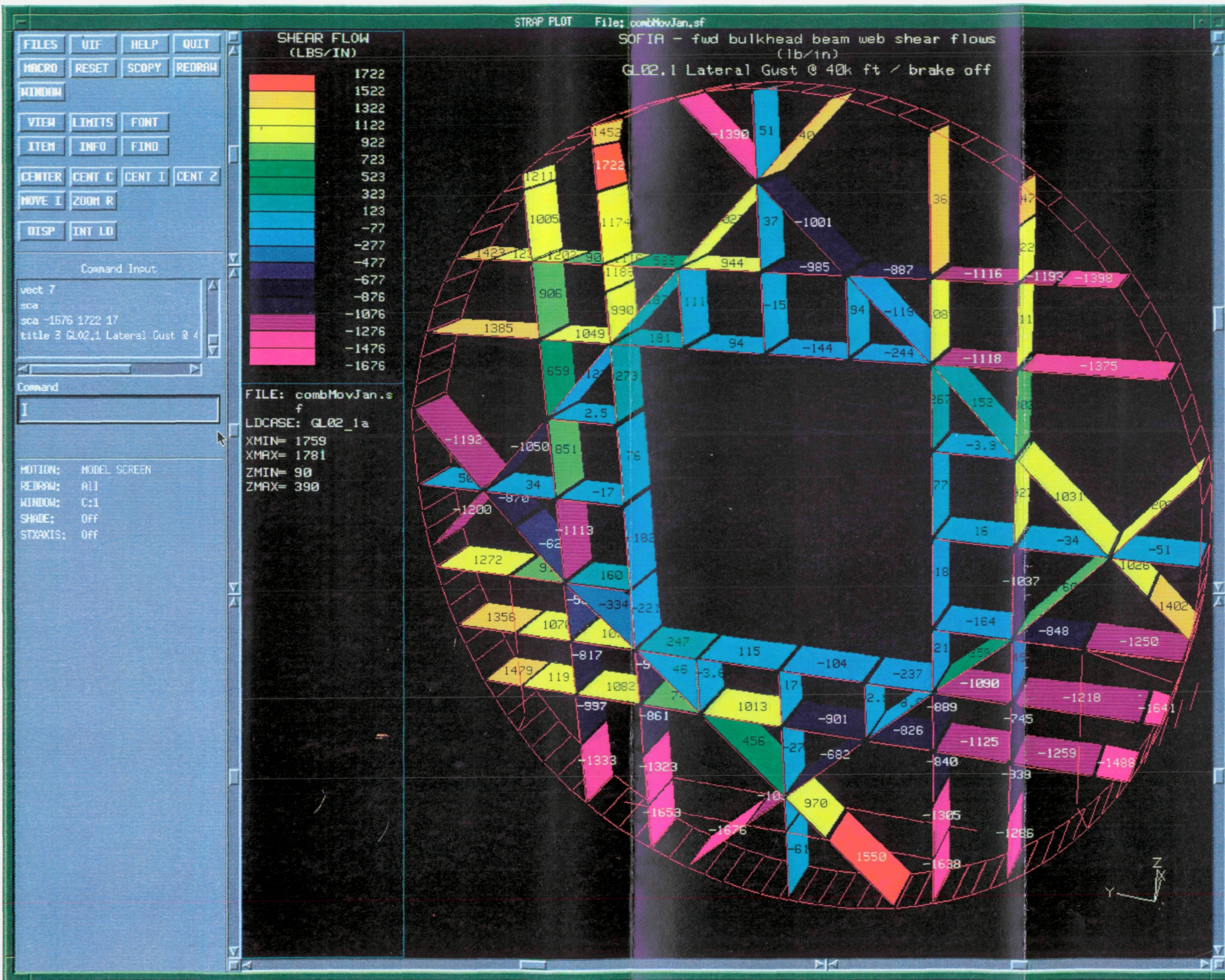
4.0 STRUCTURAL DESCRIPTION AND ANALYSIS RESULTS (cont'd)
4.1 FORWARD BULKHEAD (cont'd)

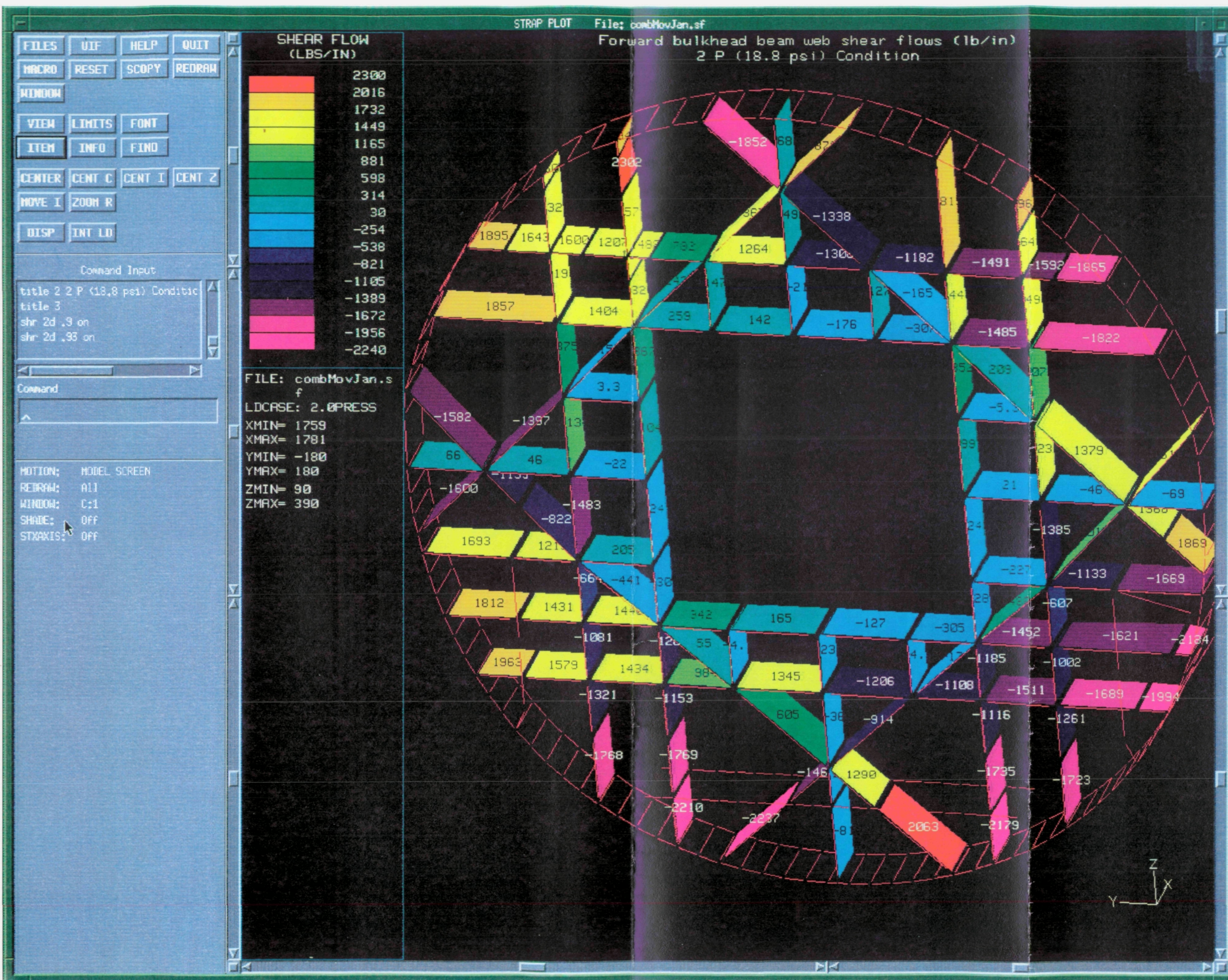
The recommended materials for this bulkhead are:

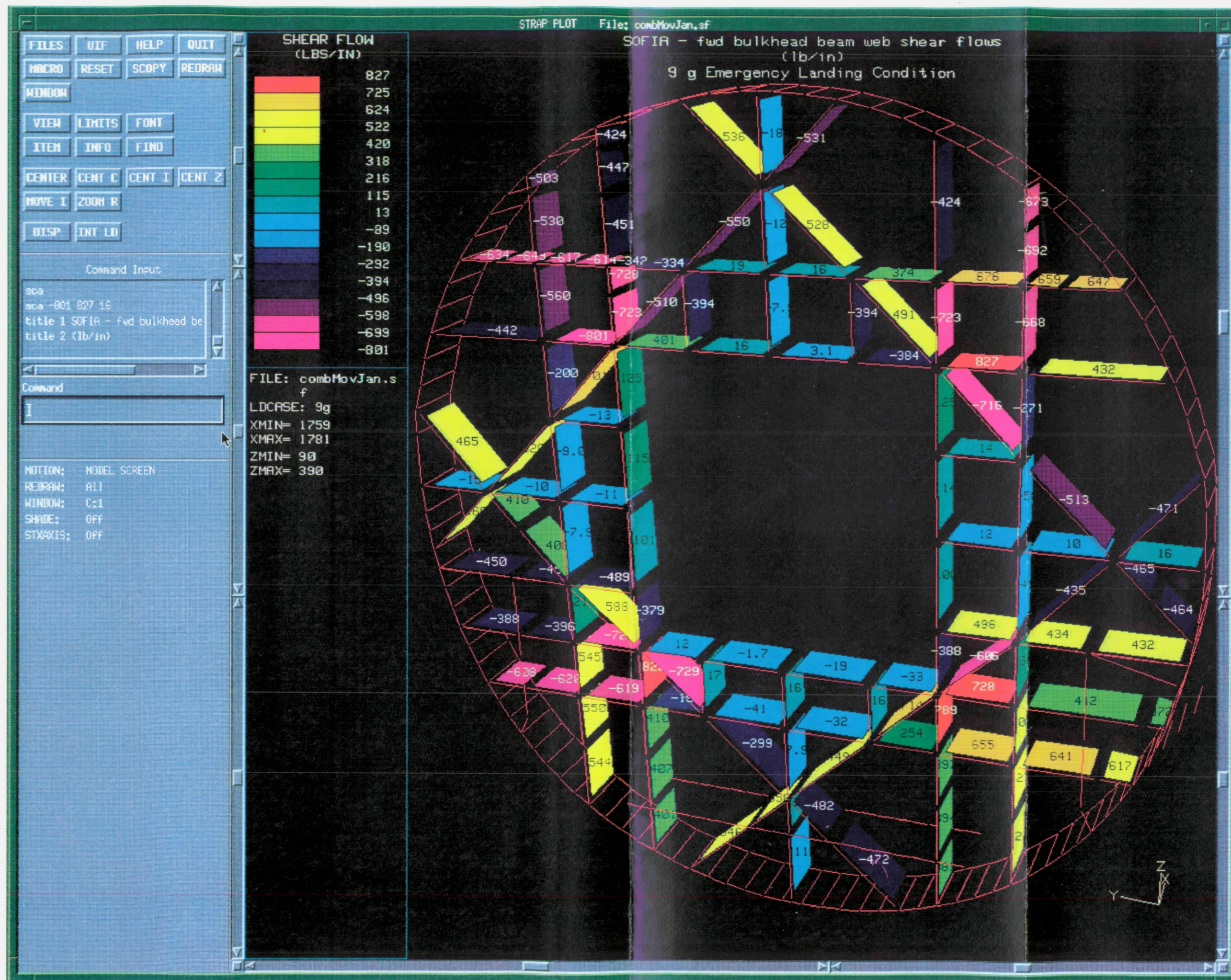
Pressure Panel	LS5150 aged to T73
Shear Beam Webs	7075 T6 Clad
Shear Beam Caps	7075 T73 Extrusion
Splice Plates	7075 T73 Plate
Splice Fittings	7075 T73 Hand Forged Billet

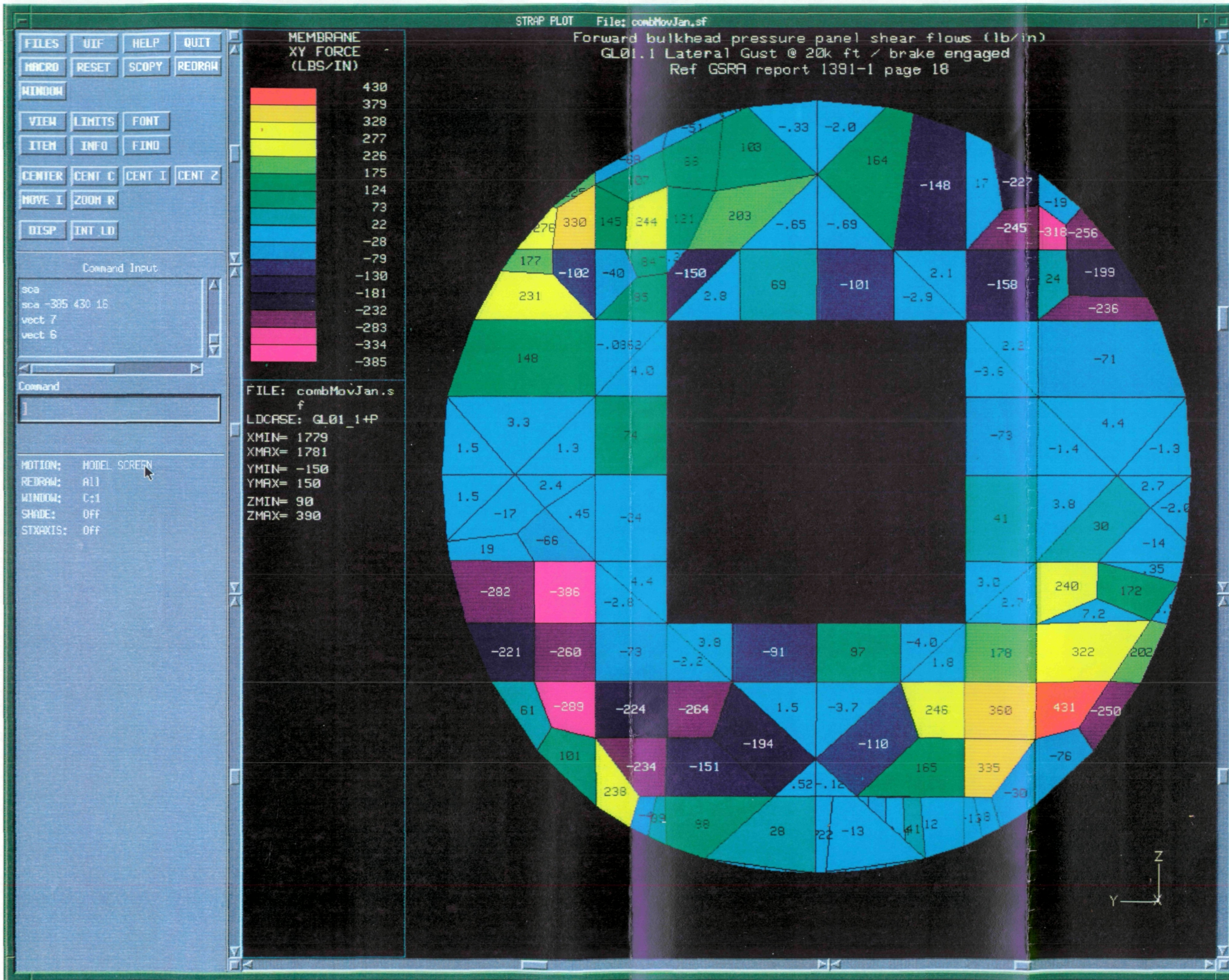
The results of the FEA model runs are summarized on the following pages as shown in the chart below:

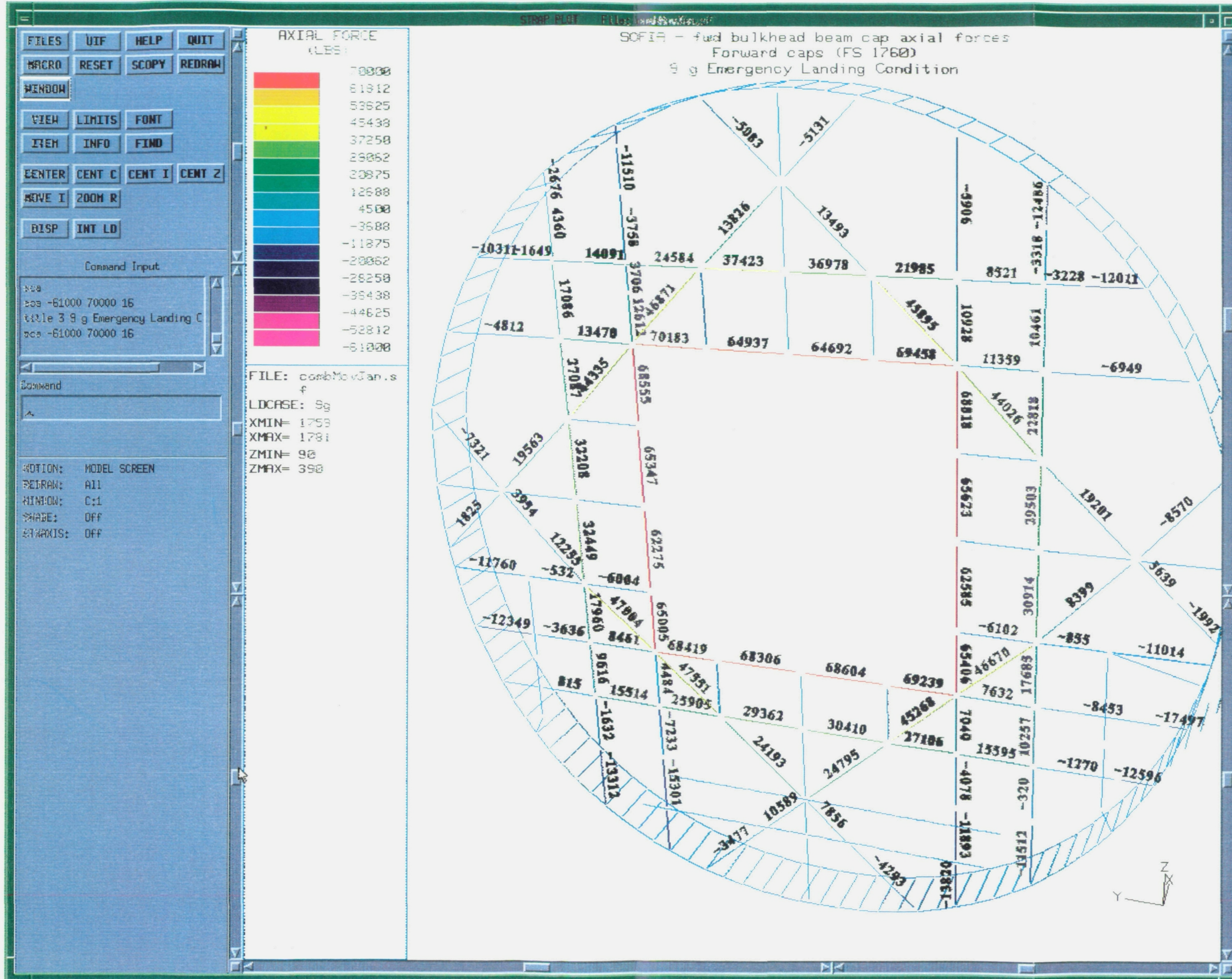
Page	Description
4.3	Beam Web Shear Flows (Ult) - Lateral Gust at 4000 ft, pressure 9.4 psi, telescope brake off.
4.4	Beam Web Shear Flows - 2P condition, cabin pressure 18.8 psi, no other loads.
4.5	Beam Web Shear Flows - Emergency Landing Condition 9g forward.
4.6	Bulkhead Pressure Web Shear Flows - Lateral Gust at 20,000 ft, telescope brake on.
4.7	Beam Cap Axial Loads, Forward Caps - Emergency Landing Condition 9g forward.
4.8	Beam Cap Axial Loads, Forward and Aft Caps, Half Bulkhead - Emergency Landing Condition 9g forward.
4.9	Beam Cap Axial Loads, Forward and Aft Caps, Half Bulkhead - Positive Gust at 20000 ft, brake engaged.
4.10	Beam Cap Axial Loads, Forward and Aft Caps, Half Bulkhead - 2P condition, 18.8 psi, no other loads.
4.11	Beam Cap Stresses, Forward Caps - 1P condition, 9.4 psi.
4.12	Beam Cap Stresses, Forward and Aft Caps, Half Bulkhead - 1P, 9.4 psi, no other loads.
4.13	Pressure Web Shear Flows - Lateral Gust at 40000 ft, brake off.
4.14	Beam Cap Areas Forward Bulkhead, Aft Face
4.15	Beam Cap Areas Forward Bulkhead, Fwd Face

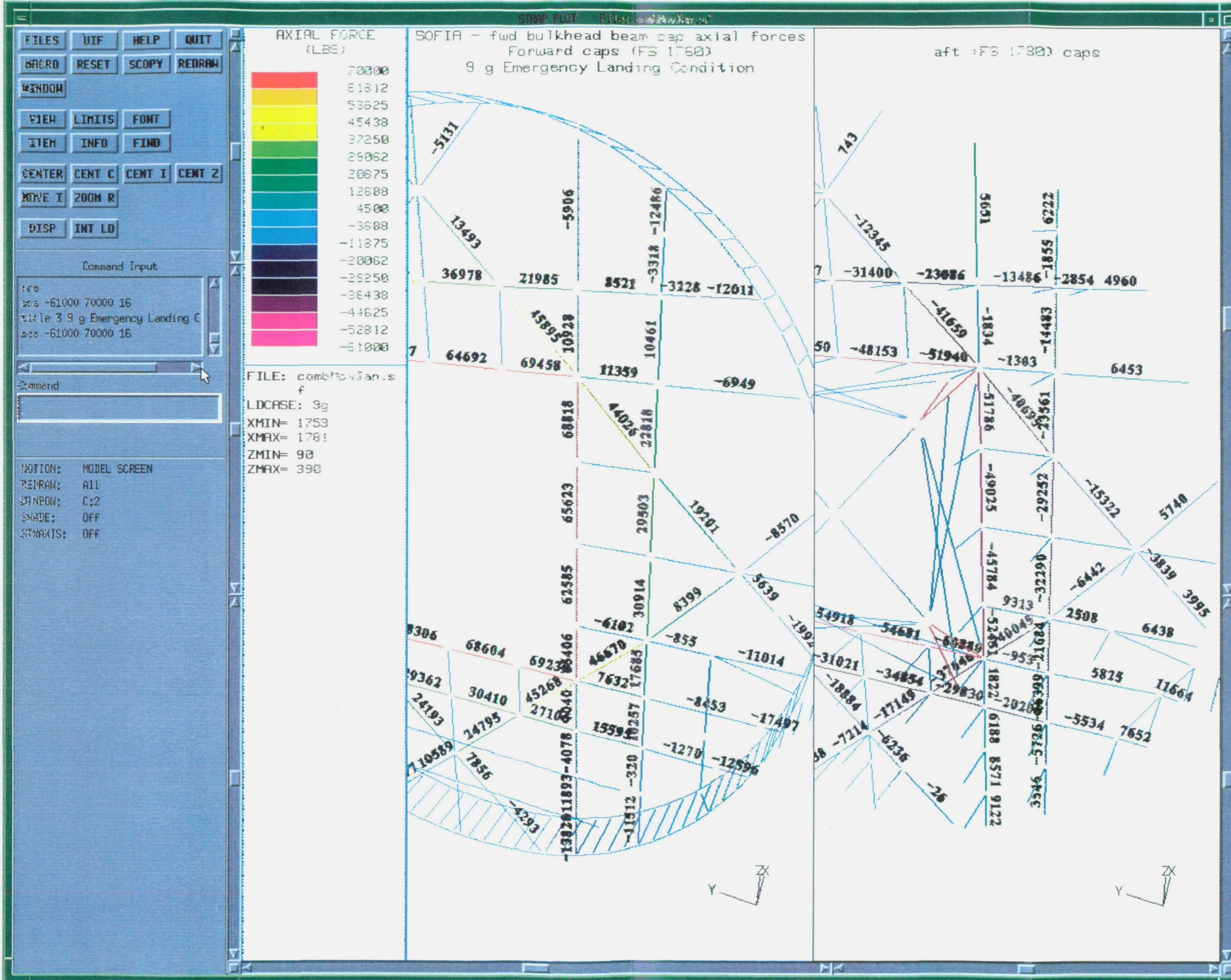


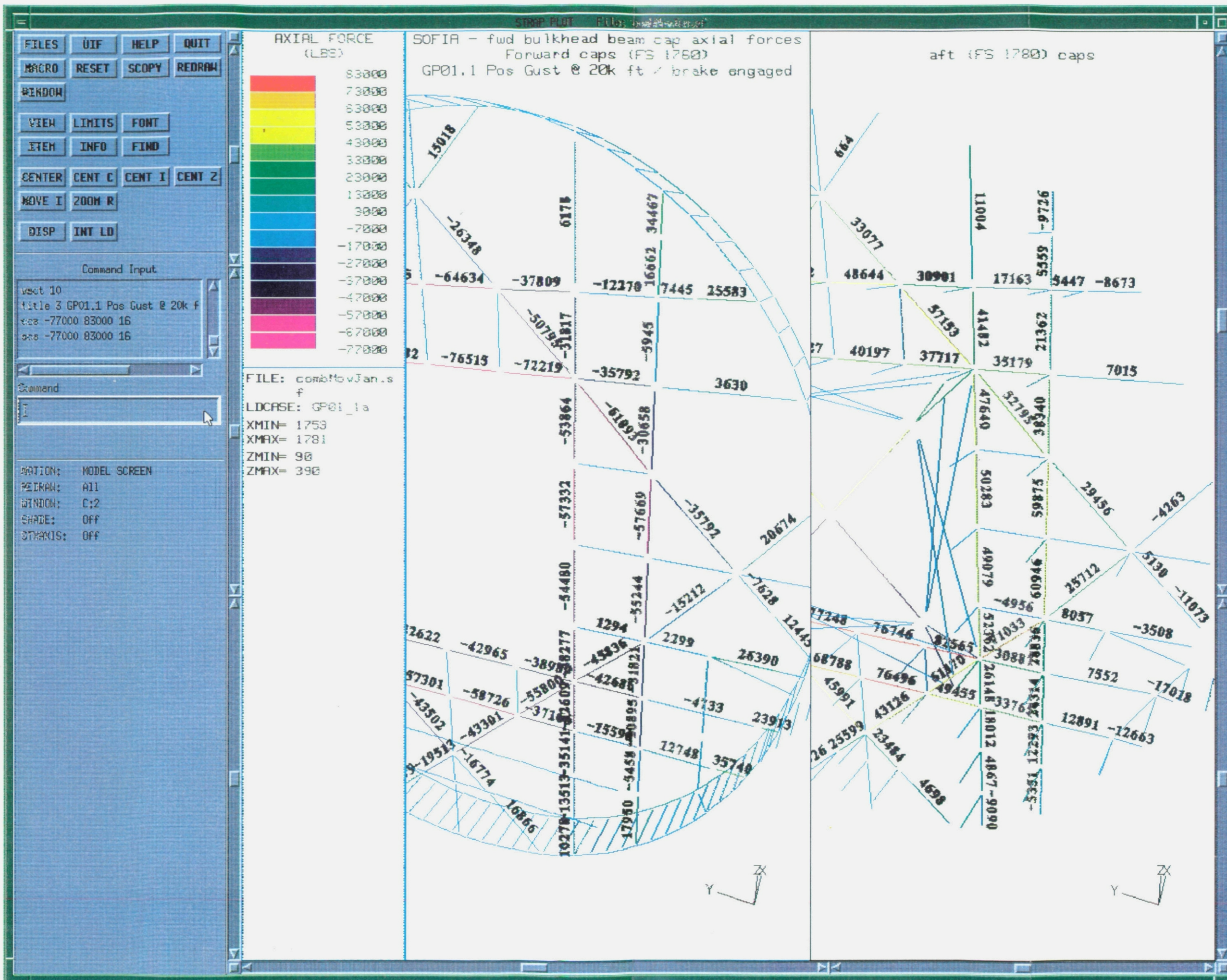


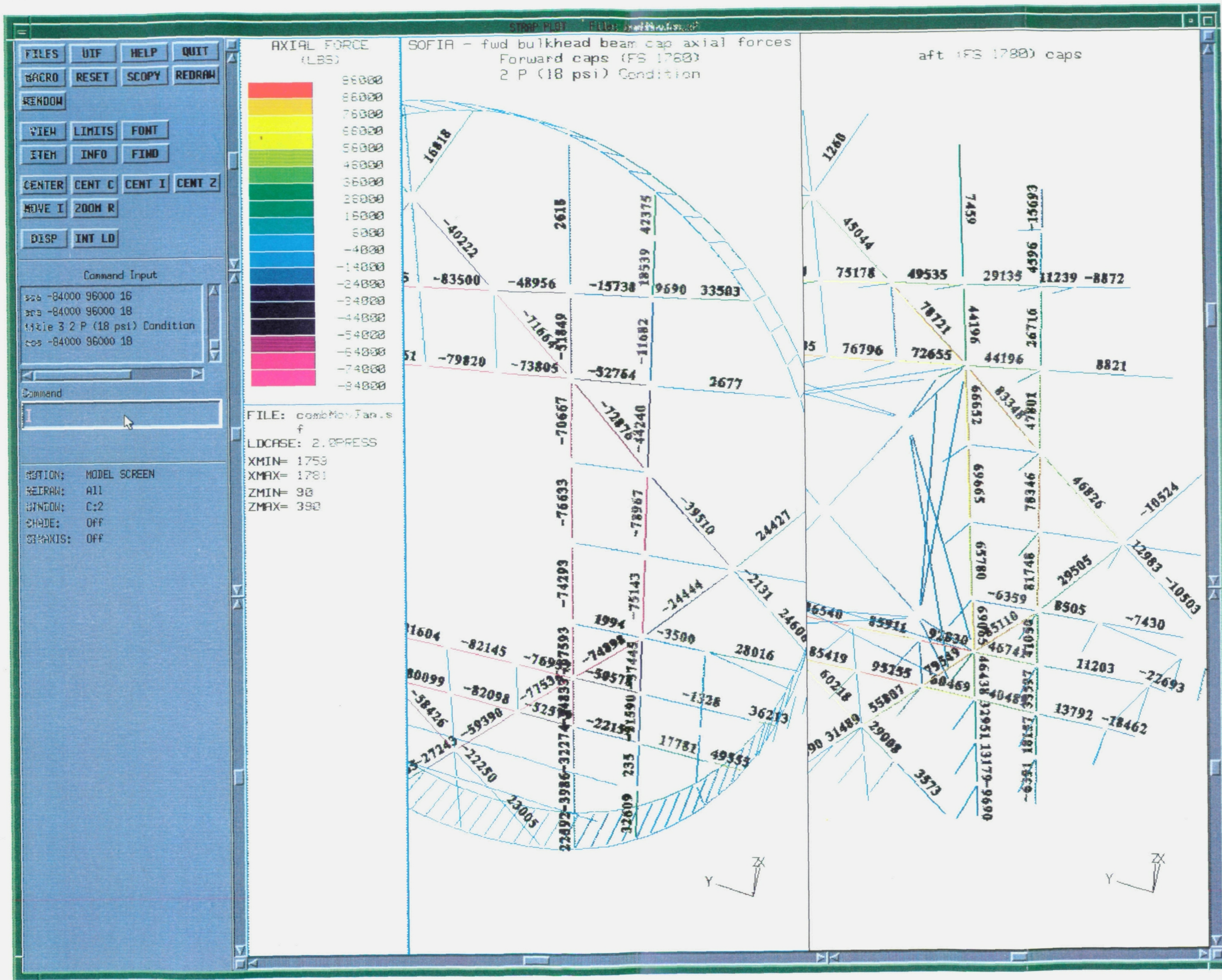


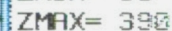








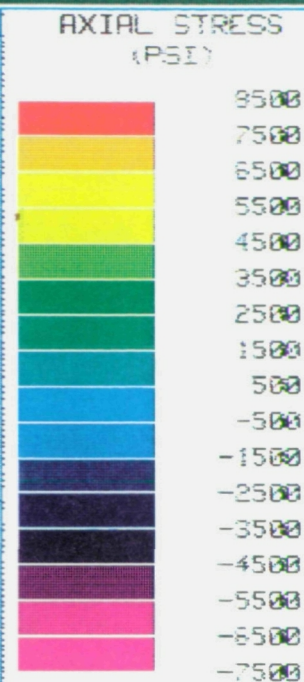




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 DISP INT LD

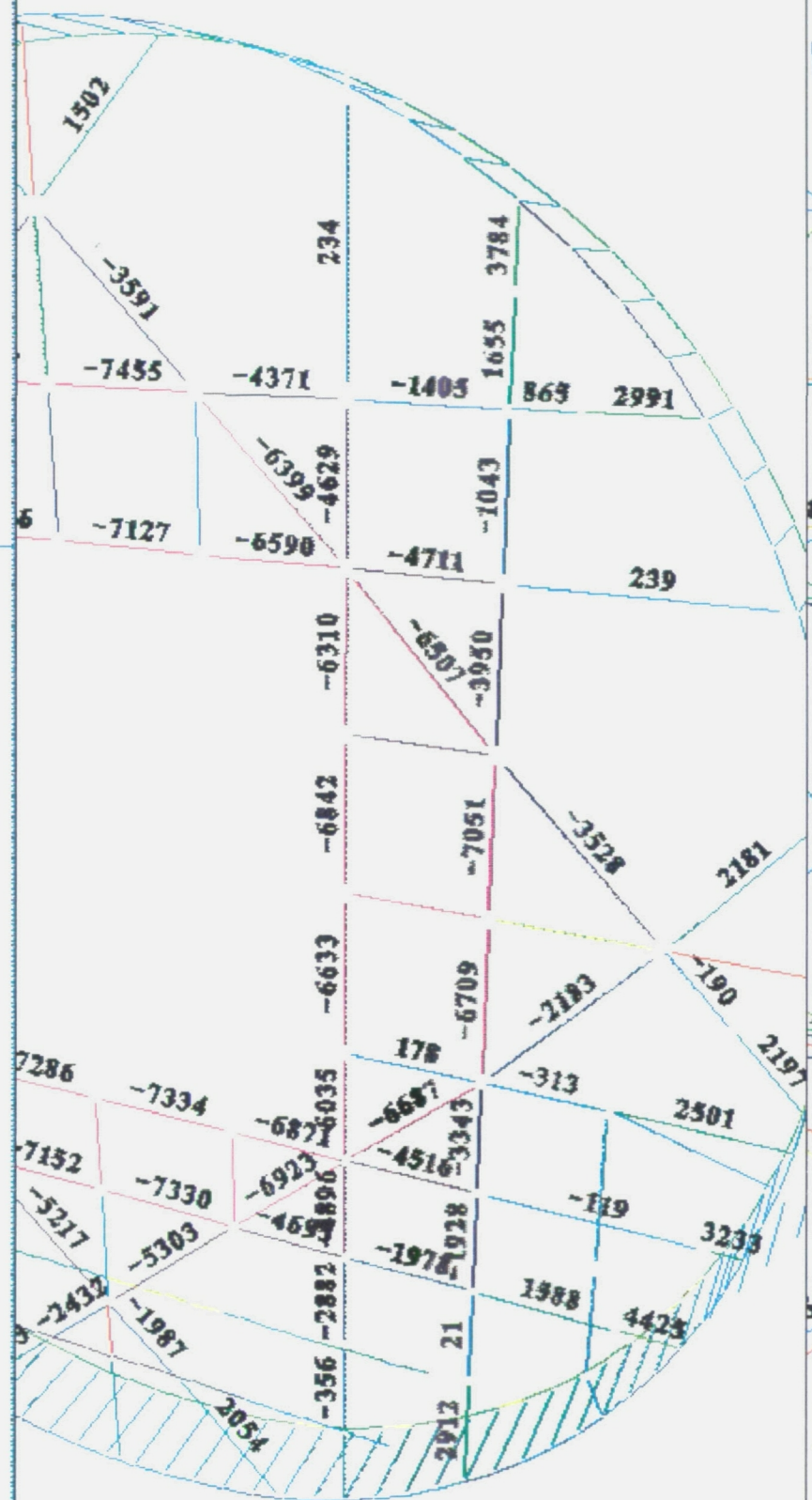
Command Input
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 xsa -7500 8500 16
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 Command

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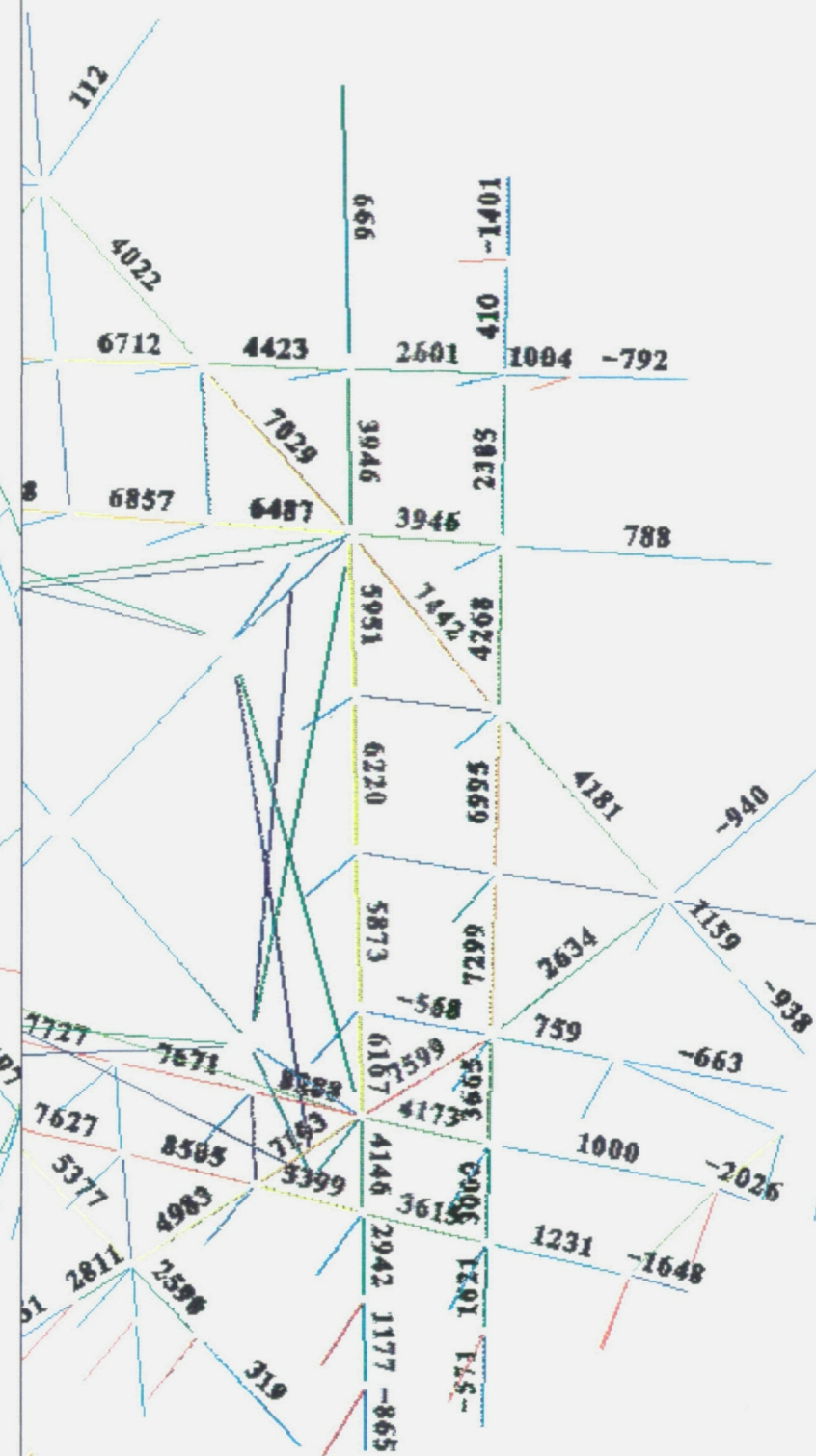


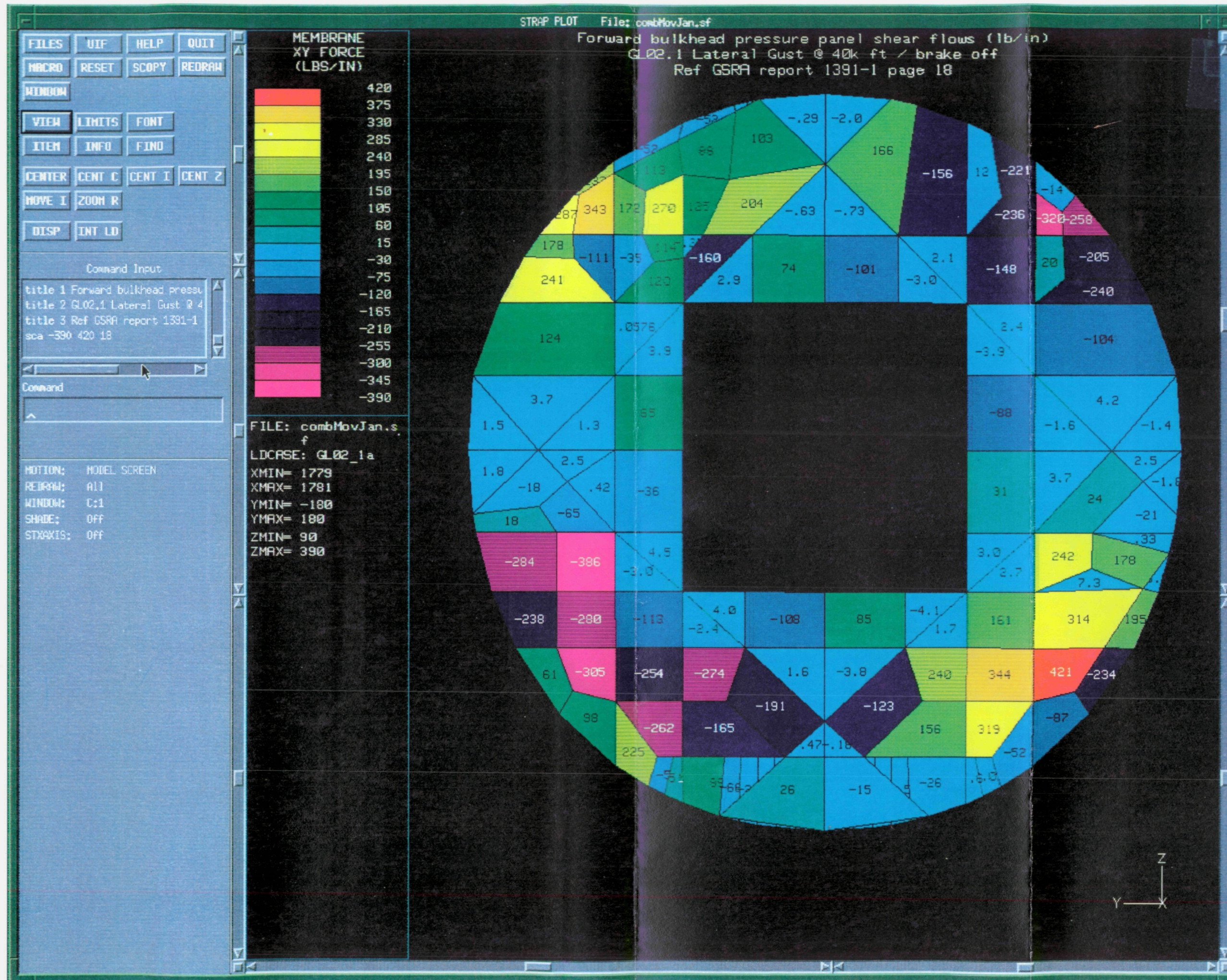
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 LDCASE: 1. OPRESS
 XMIN= 1753
 XMAX= 1781
 ZMIN= 90
 ZMAX= 390

SOFIA - fwd bulkhead beam cap axial stresses
 Forward caps (FS 1750)
 1 P (9 psi) Condition



aft (FS 1780) caps





FILES UIF HELP QUIT
 MACRO RESET SCOPY REDRAW
 RENDOM
 VIEW LIMITS FONT
 ITEM INFO FIND
 CENTER CENT C CENT I CENT Z
 MOVE I ZOOM R
 DISP INT LD

Command Input

xlin 1779 1781
 Beams are in red; Rod, green.
 title 2 Beams are in red; Rod.
 title 2 Beams are in red; Rods,

Command

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 SHADE: Off
 STYAKIS: Off

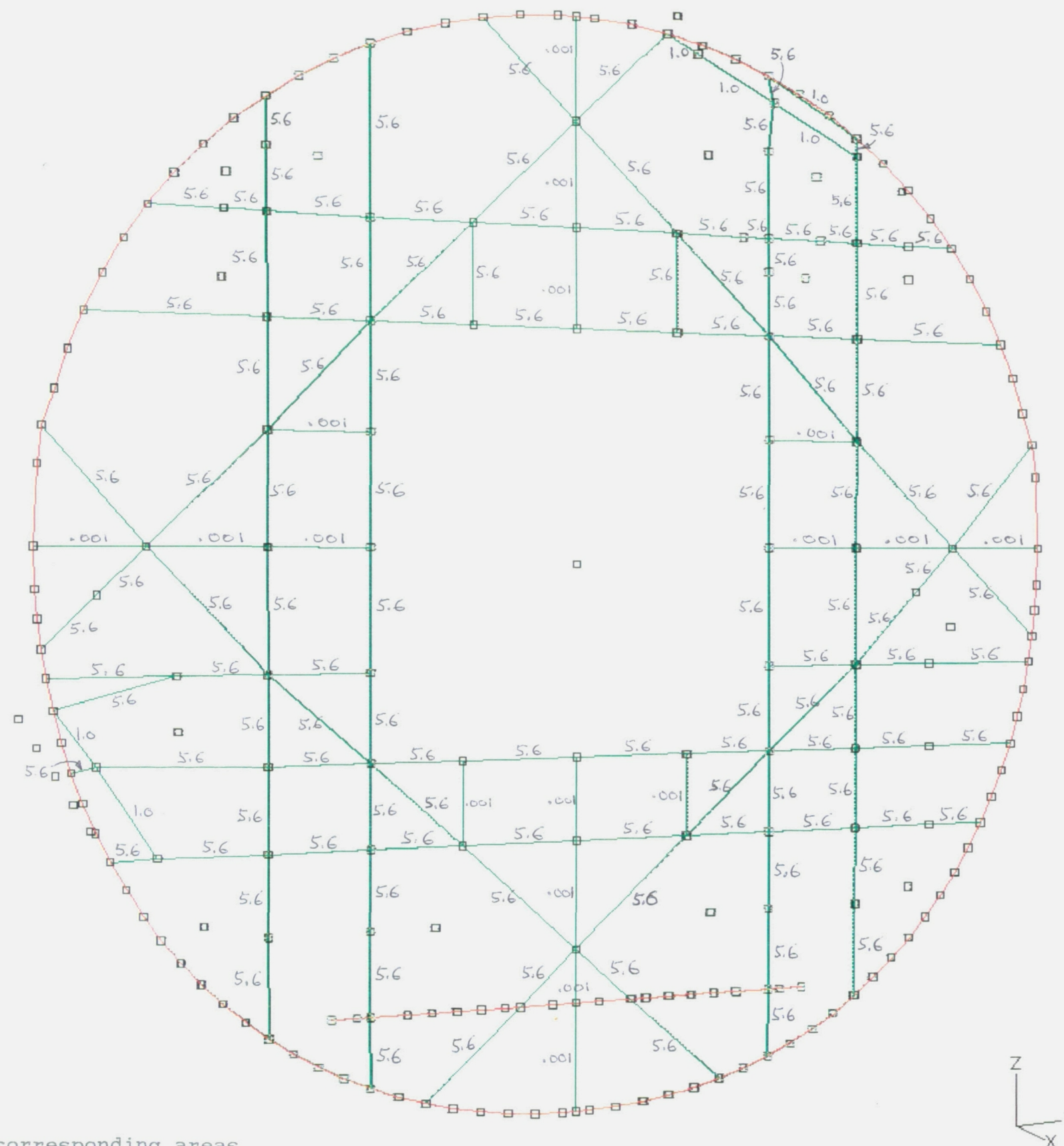
ELEMENT TYPES

BEAM
 ROD
 RIGID
 SHAPAN
 SHELL

FILE: combModJan.s
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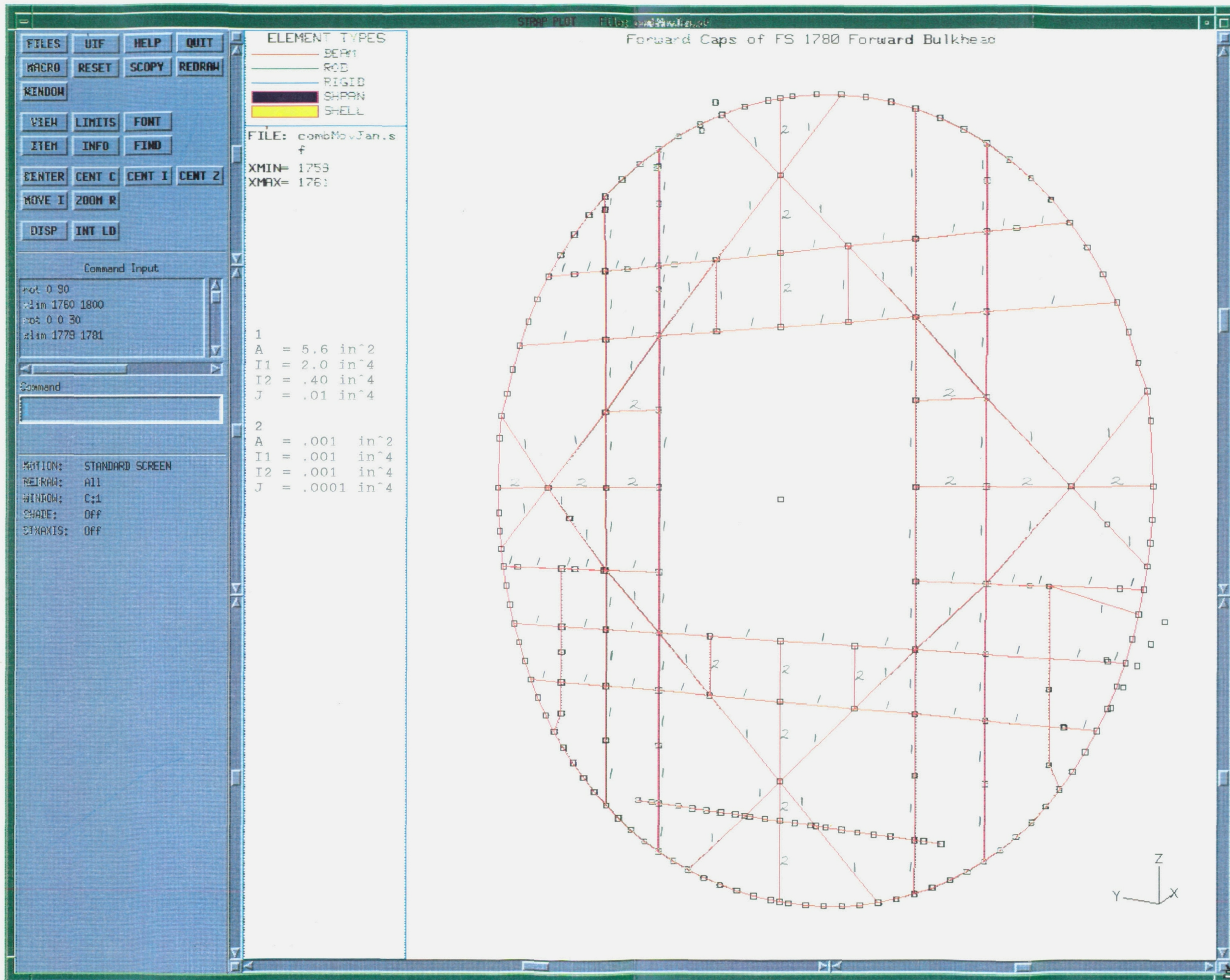
XMIN= 1779
 XMAX= 1781

Forward Bulkhead @ FS 1780
 Beams are in red; Rods, green.



Note:

Numbers indicate corresponding areas
 of rod elements in square inches.



4.0 STRUCTURAL DESCRIPTION AND ANALYSIS RESULTS (cont'd)

4.2 AFT BULKHEAD

The aft cavity bulkhead is located at FS 1960, and although of similar basic design, the structure is of less massive proportions. The four major functions of the bulkhead are:

- i) It supports the telescope brake and provides a reaction point for the brake axial and lateral forces.
- ii) It separates the telescope cavity from the unpressurized section of the aft fuselage.
- iii) It acts as the primary aft framing member for the fuselage cut-out.
- iv) It provides access, via a door, to the telescope cavity from the aft section of the fuselage for ground maintenance purpose.

As stated above the basic construction of the bulkhead is similar to the forward bulkhead although in this case beams are only 10 inches deep and are aligned vertically and horizontally only. The 45 degree members are not required as the bulkhead does not have the 100 x 100 inch cut-out and the applied differential pressure is only 1.0 psi limit. A major consideration in the design of the aft bulkhead is stiffness, as it supports the telescope brake which is assumed to be a spring loaded device. The bulkhead may not deflect relative to the forward bulkhead to a point where the brake spring loses its effectiveness. Similarly, the bulkhead should not be so stiff that, when it is engaged and the forward fuselage pressurized, the brake creates excessive forces.

The bulkhead contains a non-structural door. This door provides access to the cavity for ground maintenance and ensures a thermal seal during ground pre-cooling.

The aft bulkhead pressure web is made from the same LS5150 T73 material as that of the forward bulkhead with the risers facing forward into the cavity. The beams are also similar to those of the forward bulkhead, though only 10 inches deep and with caps of much less massive proportions. As with the forward bulkhead the beam webs are non-buckling up to limit load to obtain a constant spring rate for the telescope brake. This requires a 0.063 inch thick web with stiffeners at 5 to 6 inch spacing.

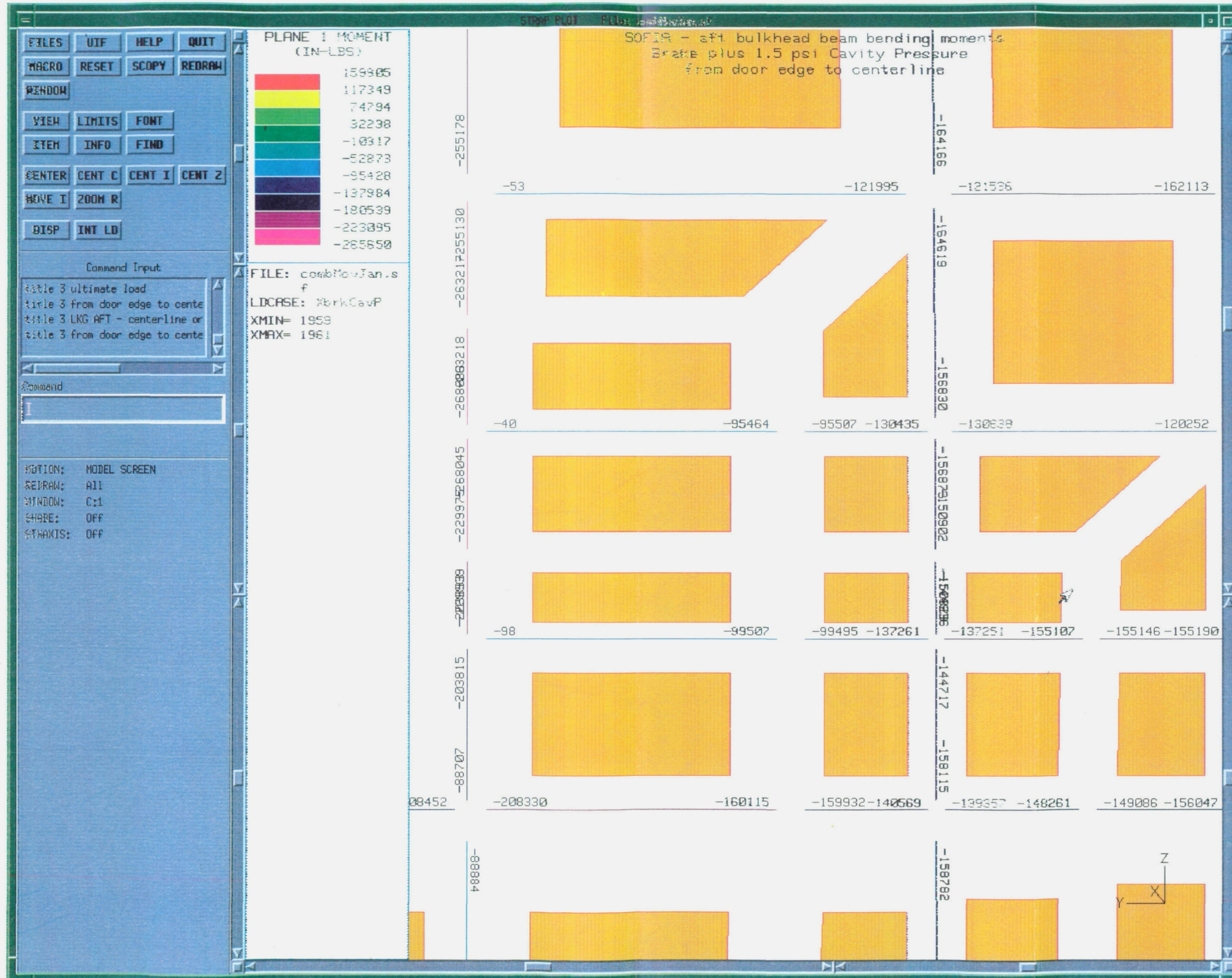
As with the forward bulkhead, the beam caps are made from 7075-T73 machined extrusion with similar joints where the vertical and horizontal beams cross. However, in this case due to the lighter loading and reduced criticality of this bulkhead, the caps are spliced using bathtub fittings only, with additional reinforcement at the door corners.

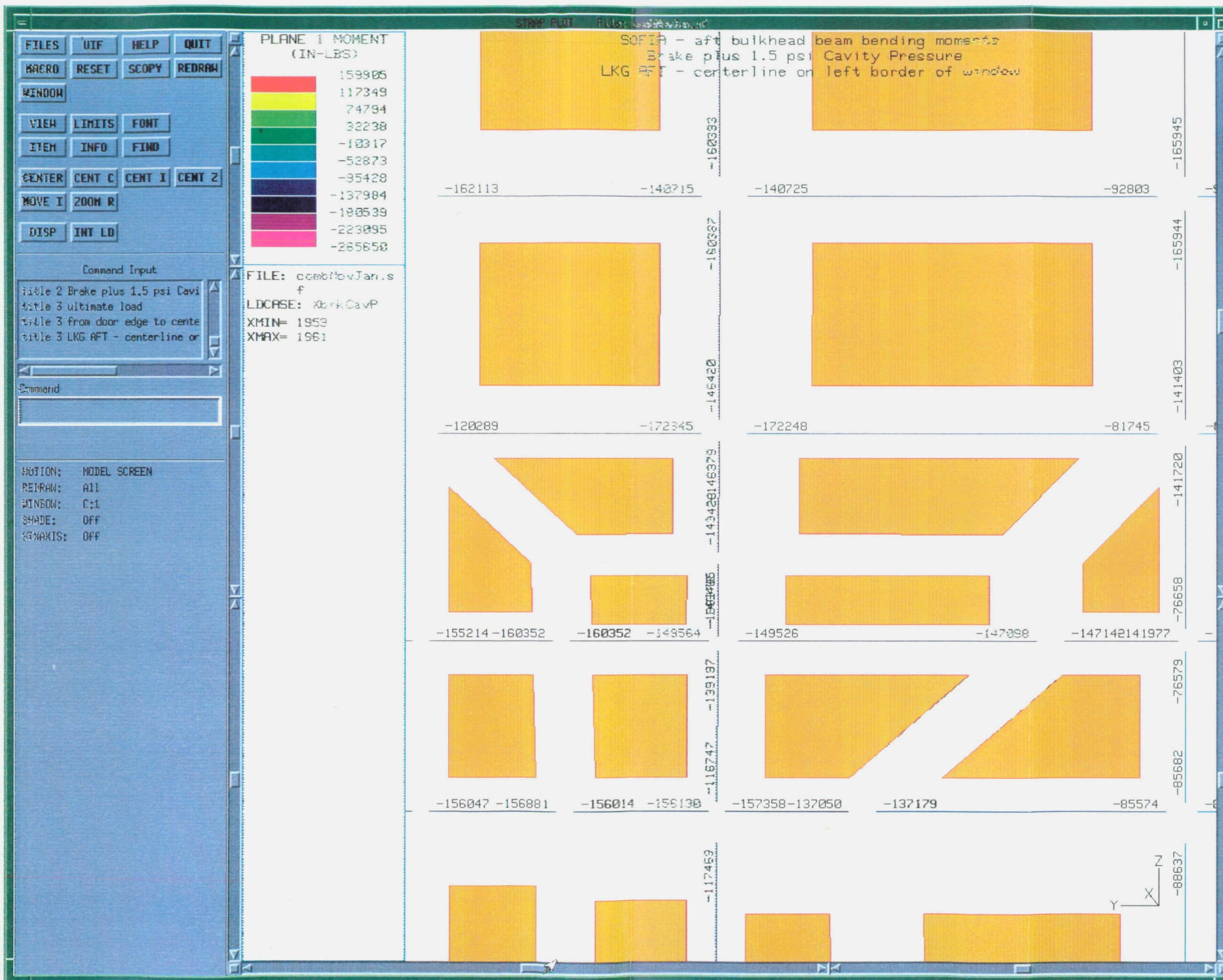
4.0 STRUCTURAL DESCRIPTION AND ANALYSIS RESULTS (cont'd)
4.2 AFT BULKHEAD (cont'd)

The recommended materials are the same as for the forward bulkhead.

The results of the FEA model runs are summarized on the following pages as shown on the chart below:

Page	Description
4.18	Bulkhead Beam Bending Moments, 1.5 psi cavity pressure with Telescope Brake on. Section at WL 200 and up between the Bulkhead Centerline and the Access Door Inboard Edge Framing Member.
4.19	Bulkhead Beam Bending Moments, 1.5 psi cavity pressure with Telescope Brake On. Section at WL 200 and up from the Bulkhead Centerline outboard (opposite to Fig page 4.16).
4.20	Bulkhead Web Shear flows. Lateral Bending Envelope Condition.
4.21	Aft Bulkhead Properties.





FILES UIF HELP QUIT
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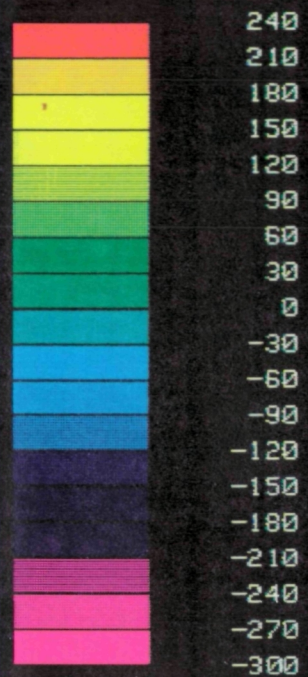
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sca -300 240 18
title 1 SOFIA - aft bulkhead sh
title 2 747 side-bending envelc

Command

I

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MEMBRANE
XY FORCE
(LBS/IN)



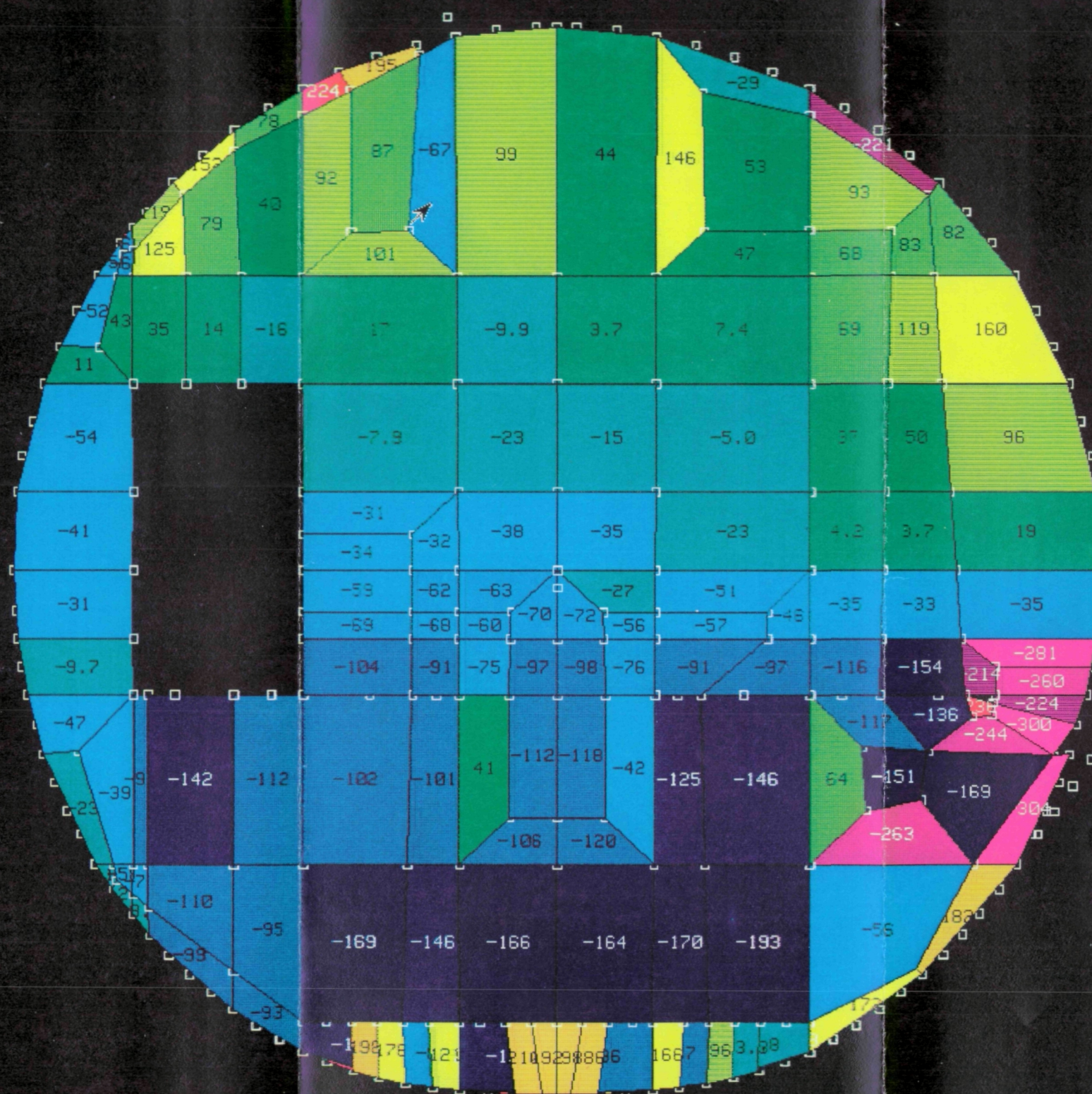
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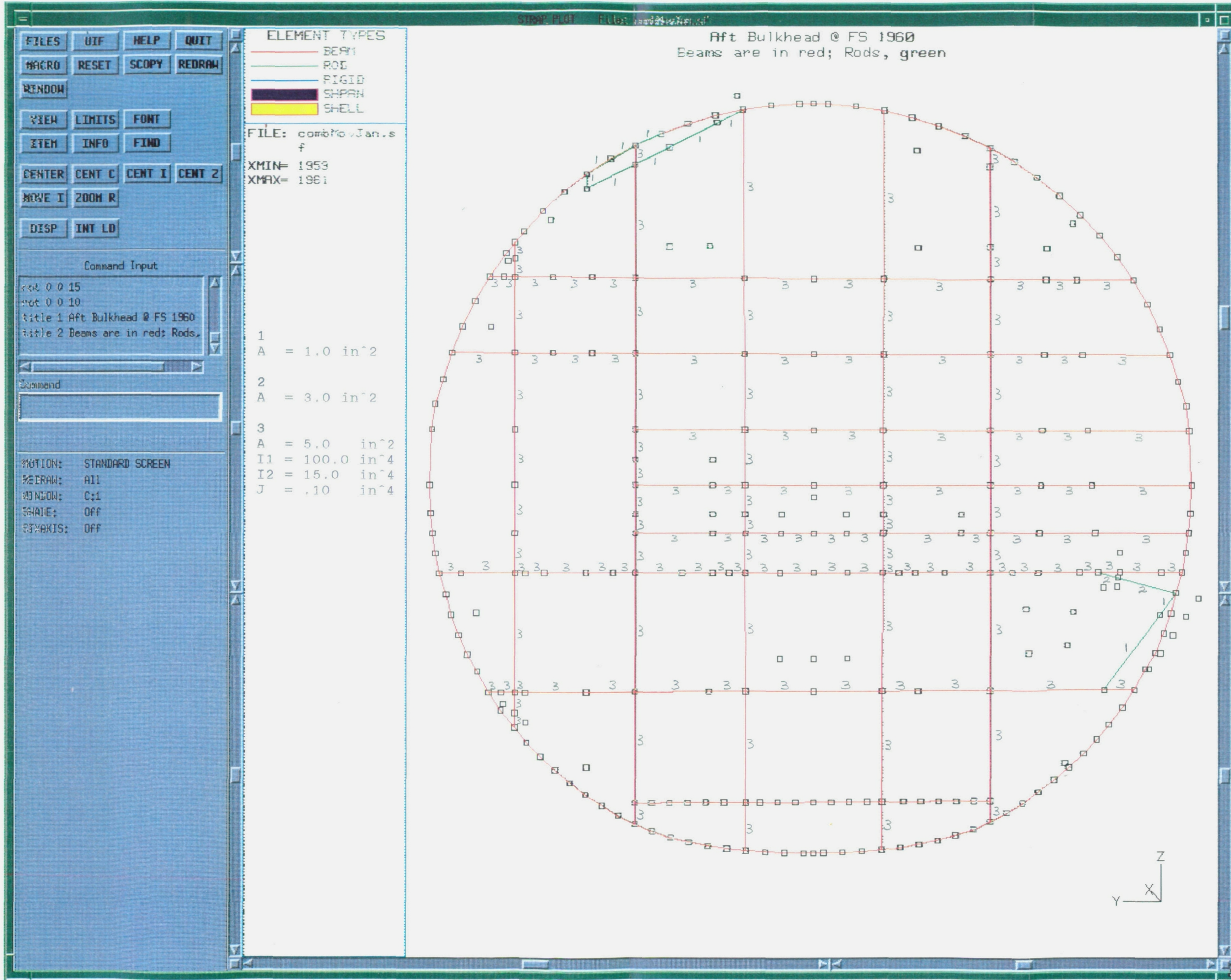
LDCASE: LateNz0

XMIN= 1959

XMAX= 1961

SOFIA - aft bulkhead shear flows
747 side-bending envelope condition





4.0 STRUCTURAL DESCRIPTION AND ANALYSIS RESULTS (cont'd)

4.3 BULKHEAD TO SHELL INTERFACE

The interface between the forward bulkhead and the fuselage shell is a critical fatigue point on the modification for two basic reasons which are closely related:

- i) The fuselage is "tied across" due to the flat bulkhead and hence is constrained against expanding under cabin pressure loads as it does forward of the bulkhead.
- ii) The bulkhead being flat deflects in bending as opposed to stretching, as is the case with a membrane type bulkhead.

These two phenomena tend to produce significant rotation between the bulkhead and the shell at the interface. To counteract this tendency, intercostals tailored to produce a gentle rate of change of slope, are used at the bulkhead beam to shell intersection. These intercostals are varied in depth and cross-sectional area, to produce relatively even rates of load change in the members and hence a good fatigue life. These intercostals were incorporated in the FEA model in gross terms except in the case of one intercostal, which for the purposes of this study was modified in more detail, and assumed to be typical. This intercostal was modeled to the point where individual fastener loads could be extracted and a Stress Severity Factor (SSF) calculated. This SSF was then factored up to account for the effect of surface finish, anodizing, and other deleterious factors to produce a Fatigue Quality Index (K). This can be used in the same manner as a Stress Concentration Factor (Kt) to make a prediction of service life. As no spectrum of SOFIA usage is available the life estimate was determined using the stresses from cabin pressurization ratioed up by 1.15 and using this as a once per flight, (ground-air-ground) loading. This is a reasonable approach as pressurization loads are generally responsible for 90% of pressurized fuselage fatigue damage.

The Stress Severity Factor (SSF) which is calculated using Lockheed Report SMN 389 is the ratio of the maximum stress in a joint to a reference stress and is a function of several factors as described below. A copy of an AIAA paper presented by Cornell and Darby describing the approach is given in Appendix A.

4.0 STRUCTURAL DESCRIPTION AND ANALYSIS RESULTS (cont'd)
4.3 BULKHEAD TO SHELL INTERFACE (cont'd)

Due to the nature of the joint under consideration the SSF equation reverts to the original equation developed by Jarfall at Boeing.

$$SSF = \frac{\alpha\beta}{f_{ref}} K_{tg} \times f_{bp} = K_{tb} \times \theta \times f_{br}$$

where $\alpha\beta$ = an empirical hole preparation and filling factor

θ = fastener tilt factor

K_{tb} = hole bearing stress concentration factor

K_{tg} = gross area axial stress concentration factor

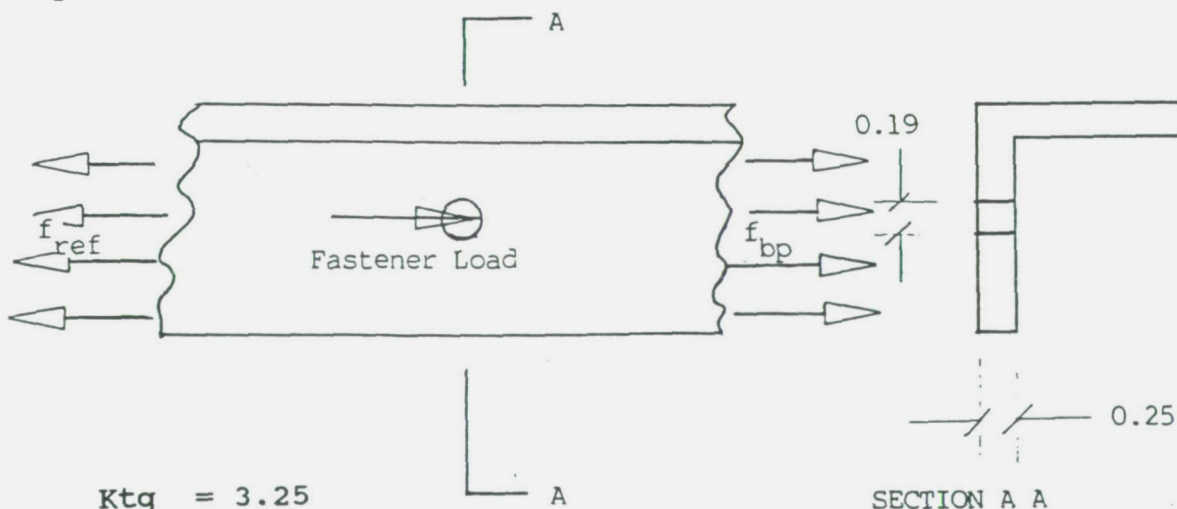
f_{br} = uniform hole bearing stress

f_{bp} = gross area uniaxial hole by-pass stress

f_{ref} = gross area uniaxial reference stress away from joint

The critical point on the intercostal occurs at fastener 13 (ref page 4.24 and 4.25 for fastener locations and local loads.)

Sample Fatigue Quality Index Calculation for fastener 13



$$K_{tg} = 3.25$$

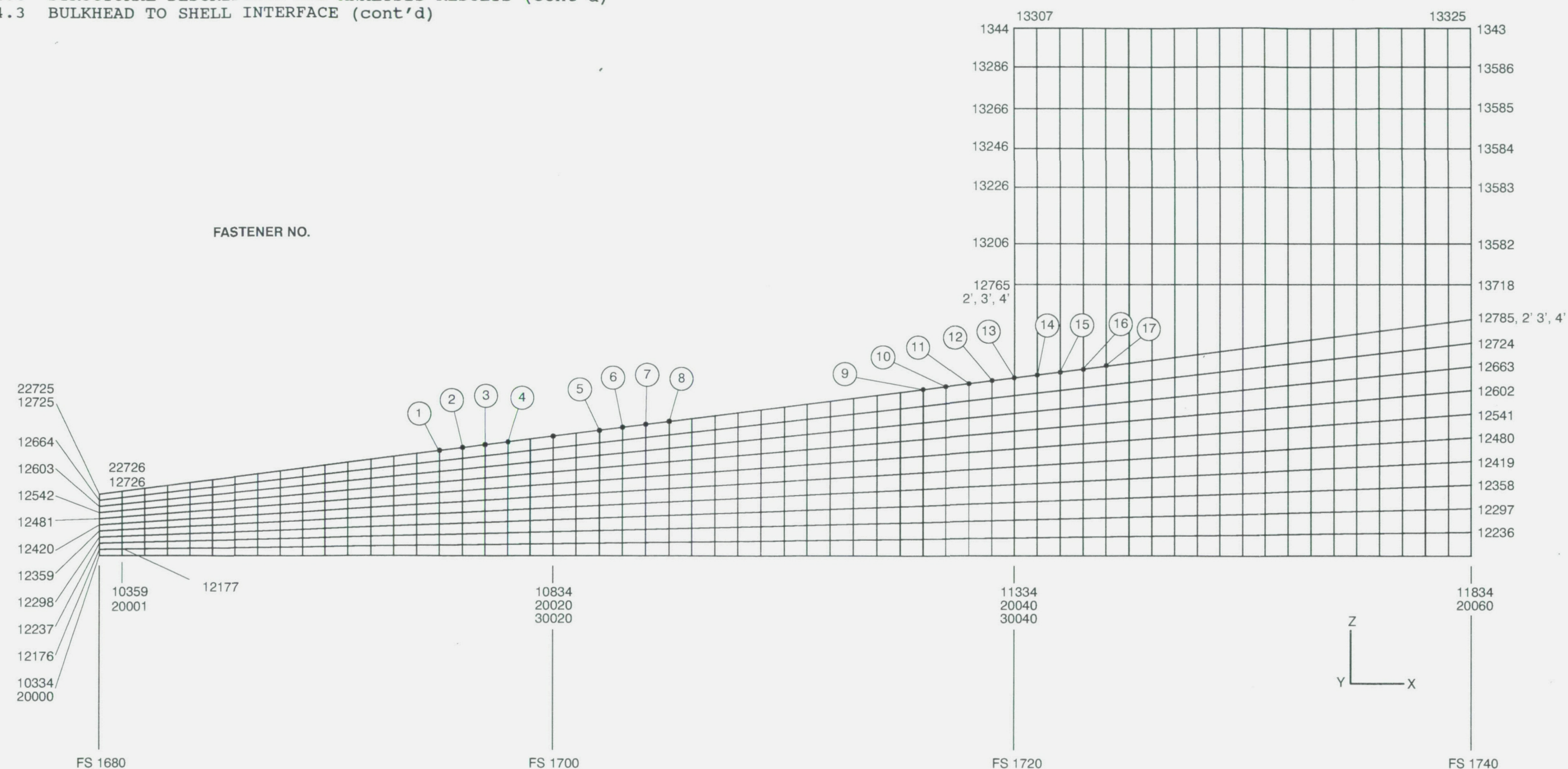
$$K_{tb} = 1.26$$

$$\theta = 1.09$$

$$\alpha\beta = 0.75$$

VIEW SHOWING HALF CAP AT FASTENER 13

4.0 STRUCTURAL DESCRIPTION AND ANALYSIS RESULTS (cont'd)
4.3 BULKHEAD TO SHELL INTERFACE (cont'd)



4.0 STRUCTURAL DESCRIPTION AND ANALYSIS RESULTS (cont'd)
4.3 BULKHEAD TO SHELL INTERFACE (cont'd)

	Elem	Area	Load	Stress	Fastener Load	
Beam	23667	0.49	730.54	1490.91	94.89	
Bcam	23668	0.49	825.04	1683.76	94.50	
Beam	23669	0.49	920.07	1877.69	95.03	
Bcam	23670	0.49	1017.99	2077.53	97.92	
Beam	23671	0.49	1121.42	2288.61	103.43	Fastener
Bcam	23672	0.49	1228.04	2506.20	106.62	Notation
Beam	23673	0.49	1337.43	2729.45	109.39	Ref p 4.24
Bcam	23674	0.49	1456.26	2971.96	118.83	1
Beam	23675	0.49	1582.25	3229.08	125.99	2
Bcam	23676	0.49	1207.85	2465.00	-374.40	3
Beam	23677	0.49	881.69	1799.37	-326.16	4
Bcam	23678	0.49	519.60	1060.41	-362.09	
Beam	23679	0.49	0.00	0.00	-519.60	
Bcam	23680	0.75	0.00	0.00	0.00	
Beam	23681	0.75	1399.70	1866.27	1399.70	
Bcam	23682	0.75	2572.59	3430.12	1172.89	5
Beam	23683	0.75	3712.41	4949.88	1139.82	6
Bcam	23684	0.75	4998.06	6664.08	1285.65	7
Beam	23685	1.00	5476.65	5476.65	478.59	8
Bcam	23686	1.00	5960.81	5960.81	484.16	
Beam	23687	1.00	6446.01	6446.01	485.20	
Bcam	23688	1.00	6932.76	6932.76	486.75	
Beam	23689	1.00	7419.65	7419.65	486.89	
Bcam	23690	1.00	7916.38	7916.38	496.73	
Beam	23691	1.00	8420.46	8420.46	504.08	
Bcam	23692	1.00	8921.65	8921.65	501.19	
Beam	23693	1.25	9436.40	7549.12	514.75	
Bcam	23694	1.25	9939.14	7951.31	502.74	
Beam	23695	1.25	10443.90	8355.12	504.76	9
Bcam	23696	1.25	10976.60	8781.28	532.70	10
Beam	23697	1.25	11530.80	9224.64	554.20	11
Bcam	23698	1.25	12105.80	9684.64	575.00	12
Beam	23699	1.25	12697.20	10157.76	591.40	13
Bcam	23700	1.25	12258.00	9806.40	-439.20	14
Beam	23701	1.25	11375.70	9100.56	-882.30	15
Bcam	23702	1.25	10561.60	8449.28	-814.10	16
Beam	23703	1.25	9810.38	7848.30	-751.22	17
Bcam	23704	1.25	9111.87	7289.50	-698.51	
Beam	23705	1.25	8455.67	6764.54	-656.20	
Bcam	23706	1.25	7831.44	6265.15	-624.23	
Beam	23707	1.25	7236.25	5789.00	-595.19	
Bcam	23708	1.25	6658.04	5326.43	-578.21	

4.0 STRUCTURAL DESCRIPTION AND ANALYSIS RESULTS (cont'd)
4.3 BULKHEAD TO SHELL INTERFACE (cont'd)

$$\begin{aligned}f_{ref} &= 10157 \text{ psi} \\f_{pb} &= 9864 \text{ psi} \\f_{br} &= 12442 \text{ psi} \\SSf &= \frac{0.75}{10157} \left(3.25 \times 9684 + 1.26 \times 1.09 \times 12442 \right) \\&= 3.59\end{aligned}$$

$$\begin{aligned}\text{Fatigue Quality Index } K &= SSF \times \text{Surface Factors} \\&= 3.59 \times 1.25 \\&= 4.48\end{aligned}$$

Increasing the reference stress by 1.15 to account for Flight Loads

$$\begin{aligned}f &= 11680 \text{ psi} \\&= 5840 + 5840\end{aligned}$$

From Lockheed SLM 16c Constant life diagrams

K	Life
2	Infinity
3	Infinity
4	$3 \times 10E6$
6	$9 \times 10E4$

By interpolation from page 4.24 for $K = 4.48$

Unfactored Life = 500000 GAG pressure cycles (flights)

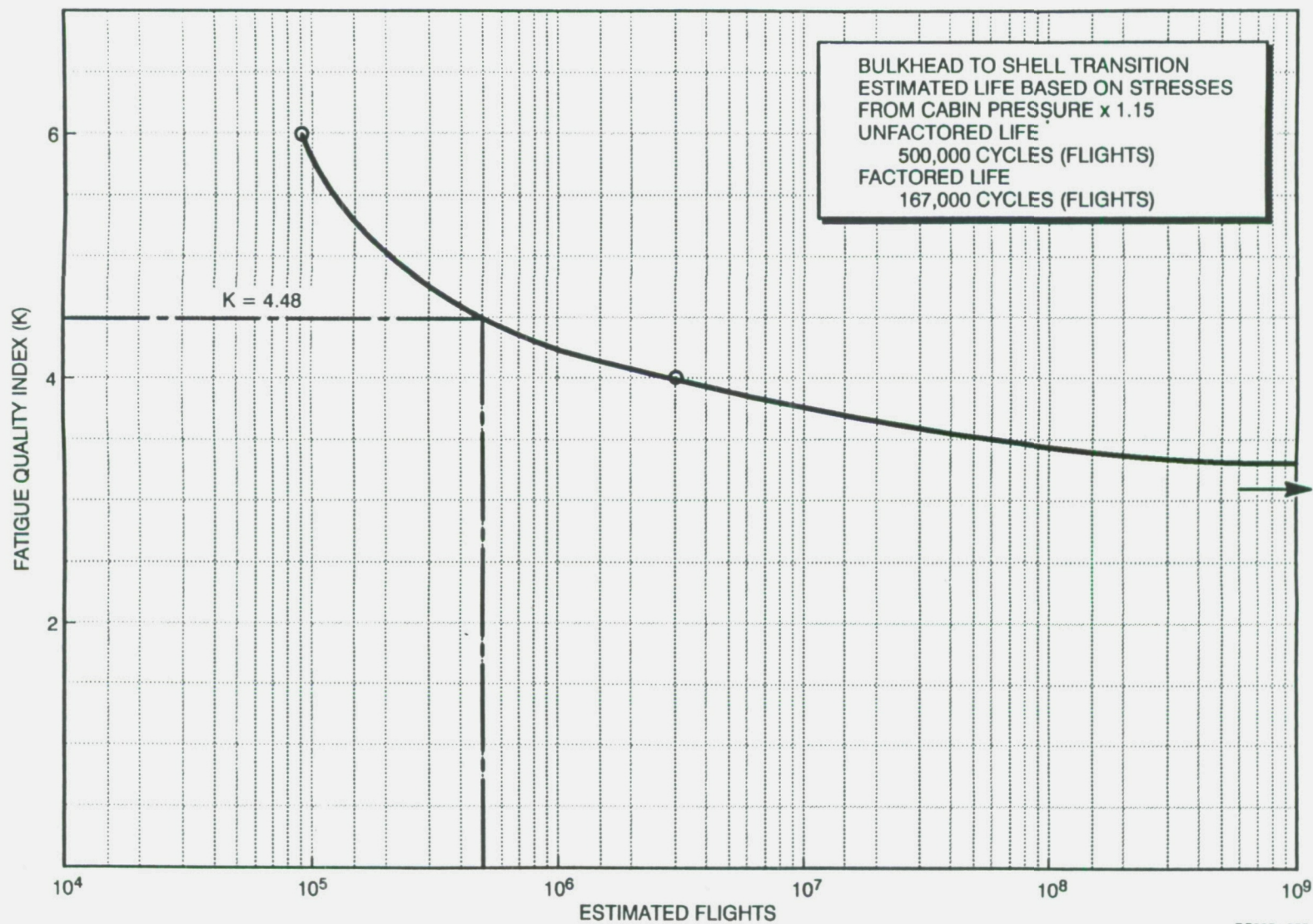
Factored Life = 167000 flights

Transition stresses and shear flows for the 9.4 psi cabin pressure condition are shown on pages 4.28 thru 4.33.

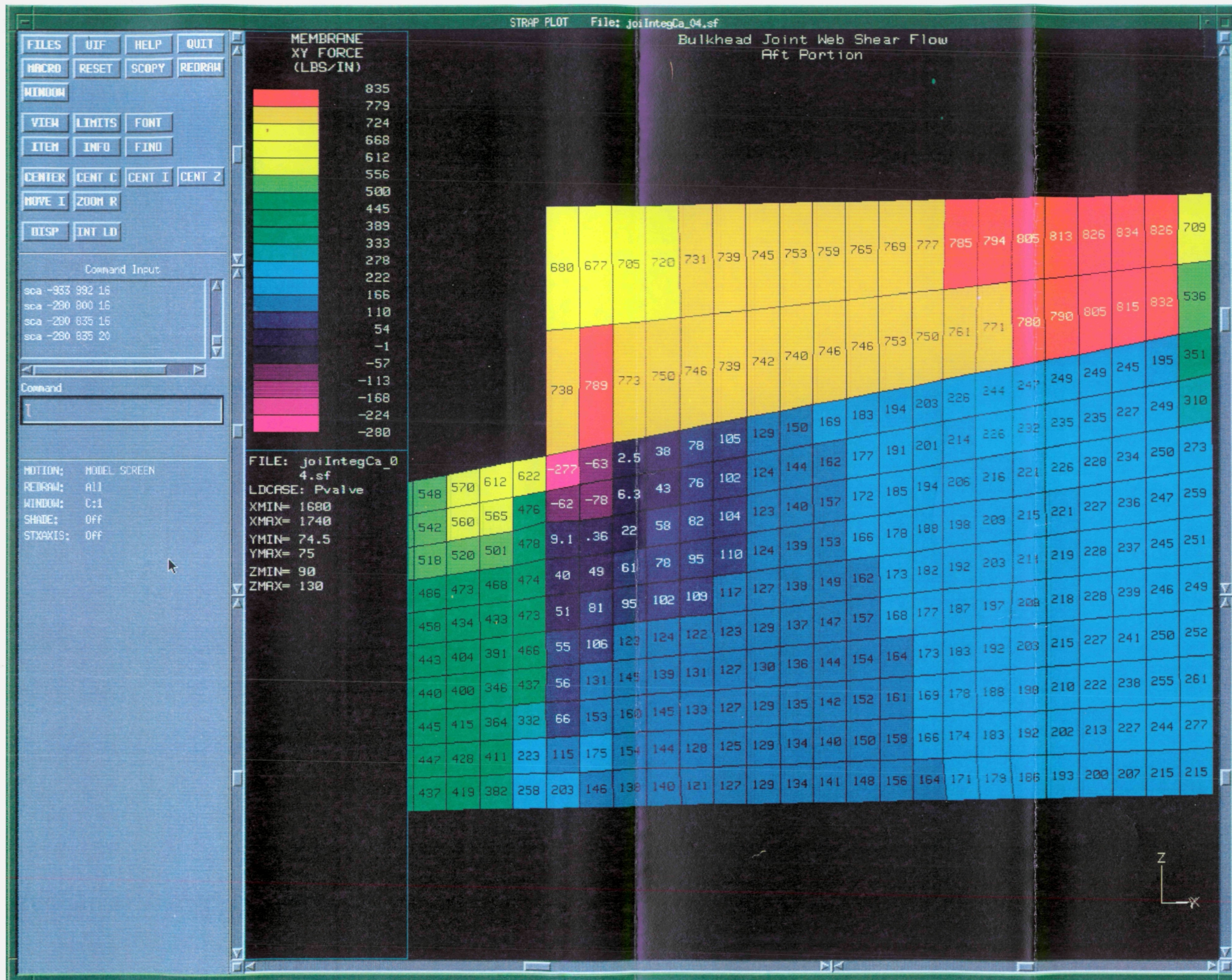
Pages 4.34 and 4.35 show the location of the transition intercostals and the bending moment diagram for the FS 1720 frame at the forward end of the intercostals.

4.0 STRUCTURAL DESCRIPTION AND ANALYSIS RESULTS (cont'd)
4.3 BULKHEAD TO SHELL INTERFACE (cont'd)

Page 4.27
Model 747
Report R54045007



PC005-062



Bulkhead Joint Web Shear Flow
Mid Portion

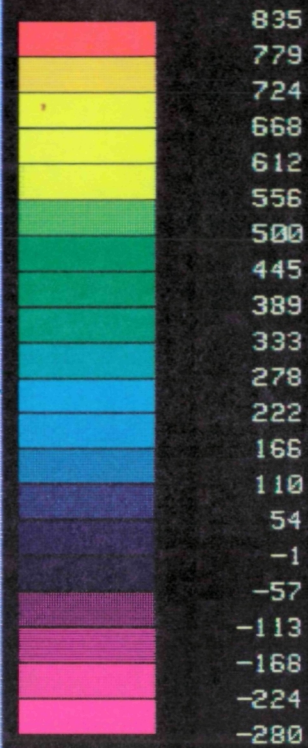
FILES VIEW HELP QUIT
MACRO RESET SCOPY REDRAW
WINDOW
VIEW LIMITS FONT
ITEM INFO FIND
CENTER CENT C CENT I CENT Z
MOVE I ZOOM R
DISP INT LD

Command Input

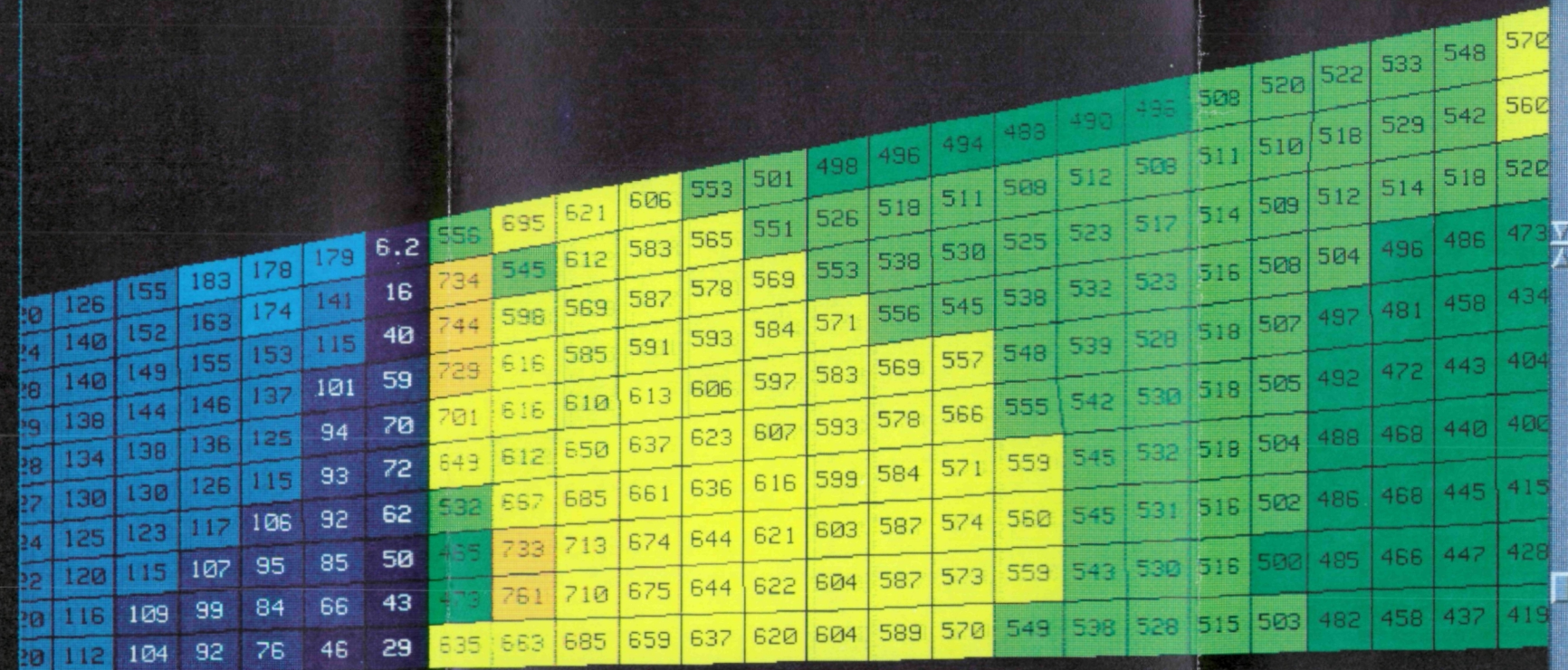
sca -290 800 16
sca -290 835 16
sca -290 835 20
title 2 Mid Portion

Command

MOTION: MODEL SCREEN
REDRAW: All
WINDOW: C:1
SHADE: Off
STXAXIS: Off

MEMBRANE
XY FORCE
(LBS/IN)

FILE: joiIntegCa_0
4.sf
LDCASE: Pvalve
XMIN= 1680
XMAX= 1740
YMIN= 74.5
YMAX= 75
ZMIN= 90
ZMAX= 130

Z
X

FILES UIF HELP QUIT
MACRO RESET SCOPY REDRAW
WINDOW
VIEW LIMITS FONT
ITEM INFO FIND
CENTER CENT C CENT I CENT Z
MOVE I ZOOM R
DISP INT LD

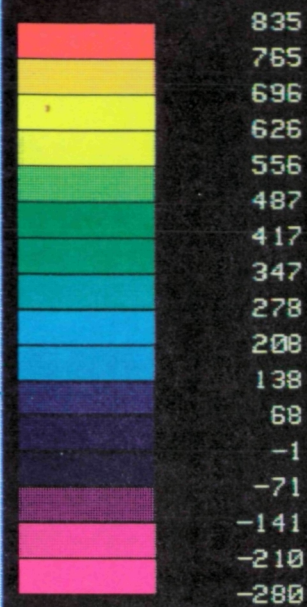
Command Input

title 2 Aft Portion
title 1 Bulkhead Joint Web Shear
title 2 Forward Portion
sca -280 835 15

Command

MOTION: MODEL SCREEN
REDRAW: ALL
WINDOW: C:1
SHADE: OFF
STYAXIS: OFF

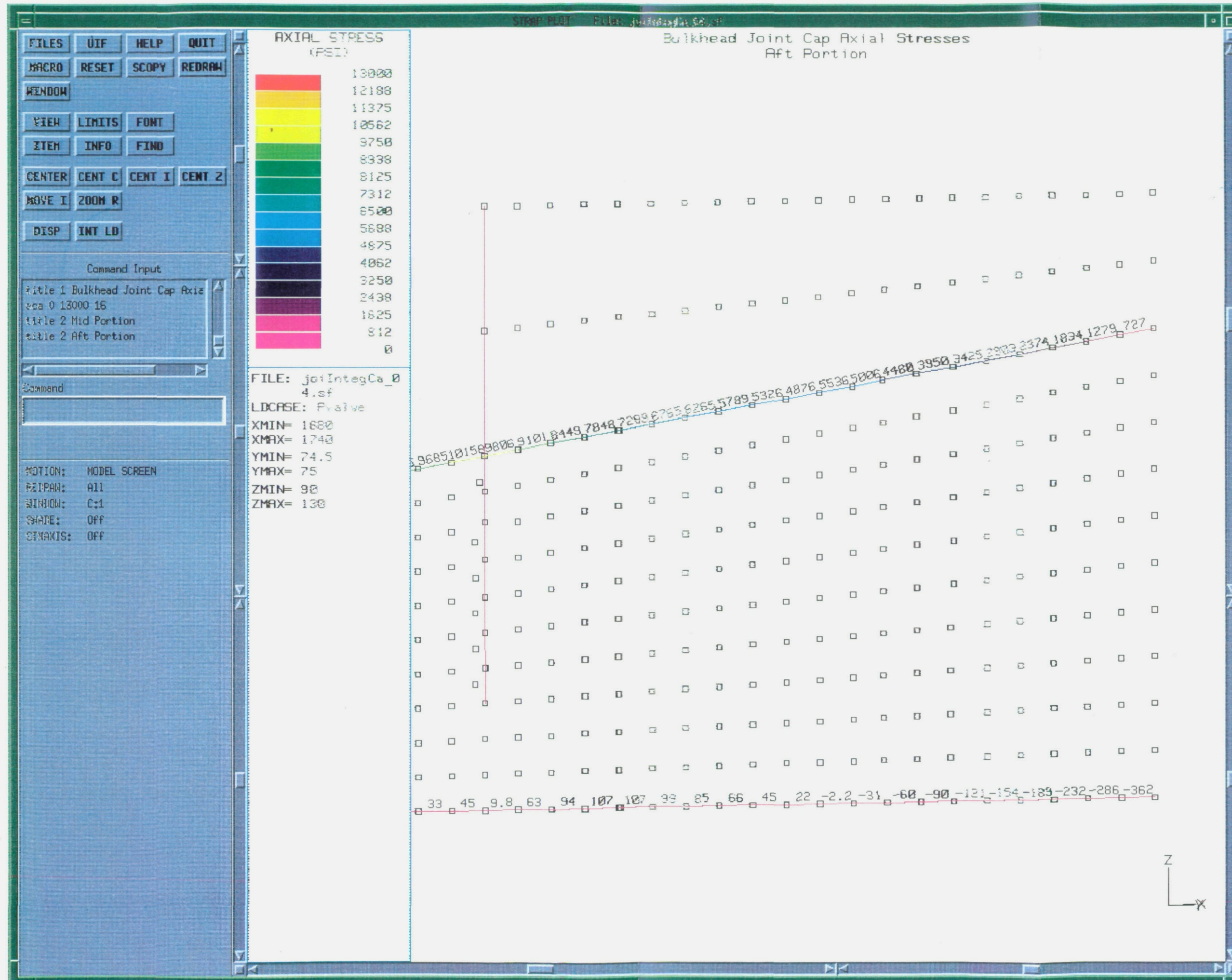
MEMBRANE
XY FORCE
(LBS/IN)

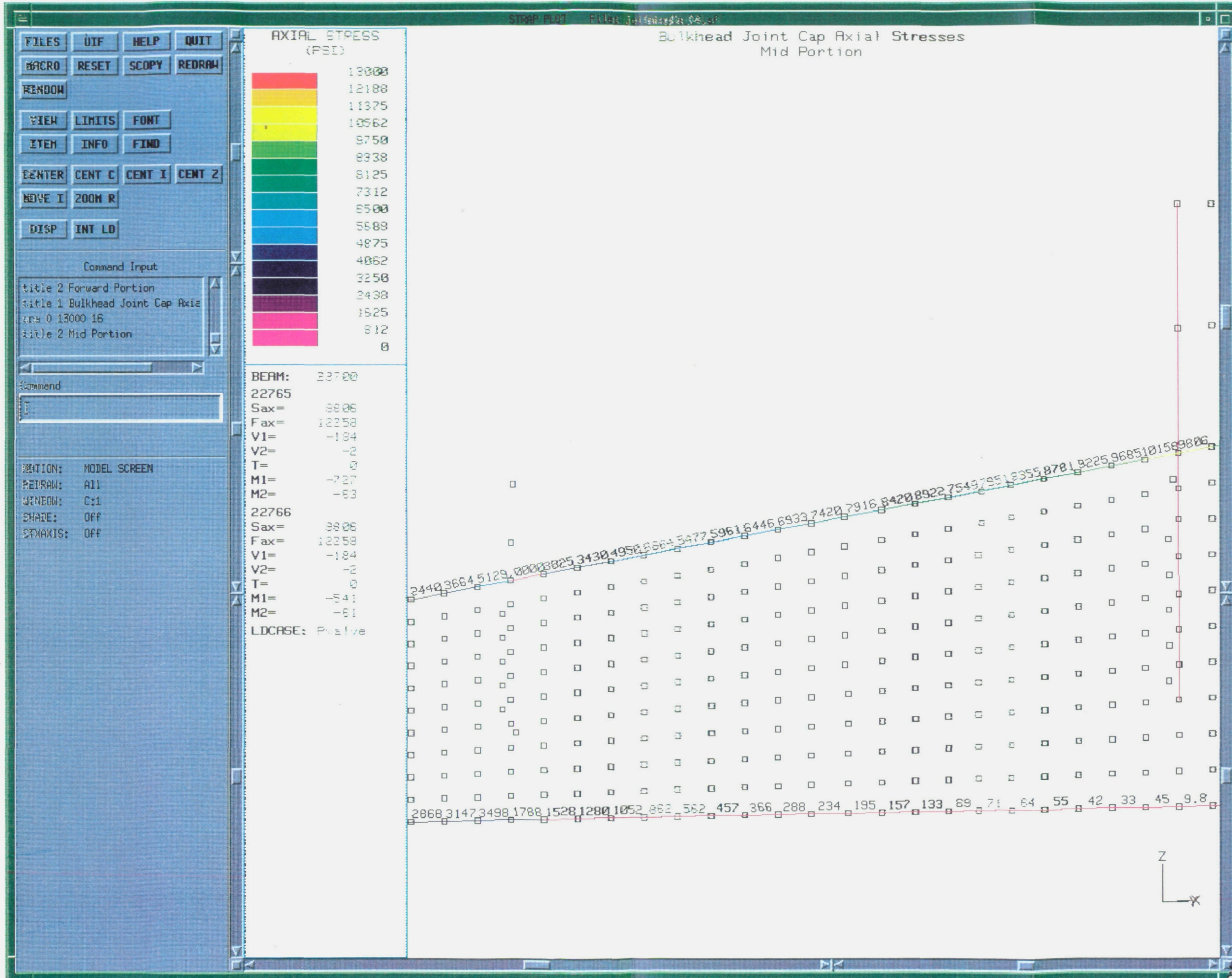


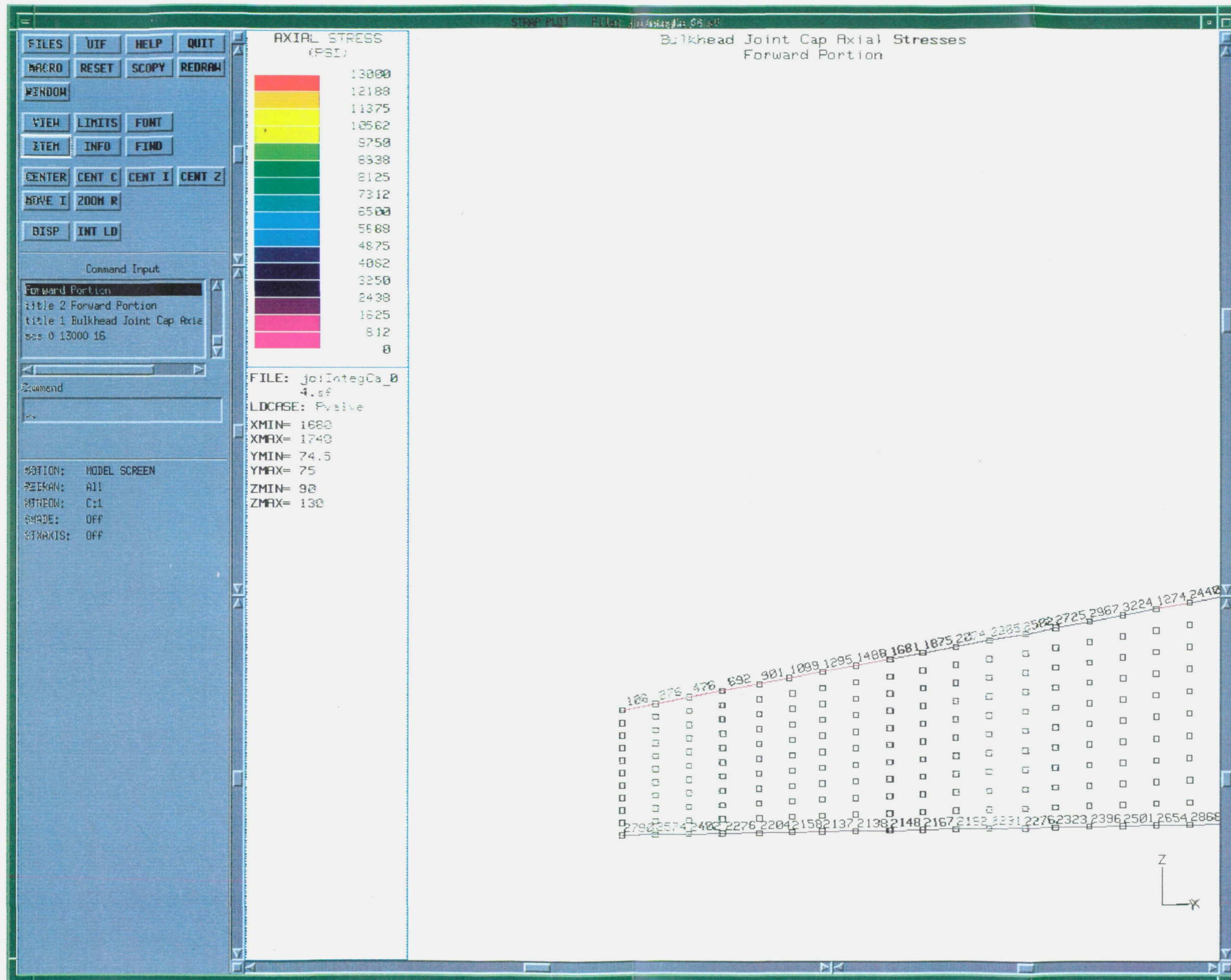
FILE: joiIntegCa_0
4.sf
LDCASE: Pvalve
XMIN= 1680
XMAX= 1740
YMIN= 74.5
YMAX= 75
ZMIN= 90
ZMAX= 130

83	95	107	105	106	100	97	97	96	98	100	106	112	120	126	155	183	178
67	113	115	115	108	104	102	101	101	102	105	112	115	124	140	152	163	174
63	120	127	121	113	107	106	105	104	106	110	115	119	128	140	149	155	153
64	127	135	127	117	111	109	108	108	110	113	117	121	129	138	144	146	137
70	135	142	132	124	117	116	115	115	116	118	120	122	127	130	130	126	115
81	144	147	135	127	120	119	118	117	118	120	121	122	124	125	123	117	106
97	155	149	137	129	123	122	120	120	120	121	122	121	122	120	115	107	95
121	164	148	138	129	127	125	123	123	123	123	123	121	120	116	109	99	84
156	169	140	141	133	132	128	125	126	126	124	122	123	120	112	104	92	76
223	133	151	132	133	132	128	125	126	126	124	122	123	120	112	104	92	76

Z
X







FILES VIEW HELP QUIT
MACRO RESET SCOPY REDRAW
WINDOW
VIEW LIMITS FONT
ITEM INFO FIND
CENTER CENT C CENT I CENT Z
MOVE I ZOOM R
DISP INT LD

Command Input

vec 3
xra -200000,20000 3
xra -200000,200000 3
vec 1

Command

NOTION: MODEL SCREEN
REDRAW: All
MINION: C:1
SHADE: Off
STYAXIS: Off

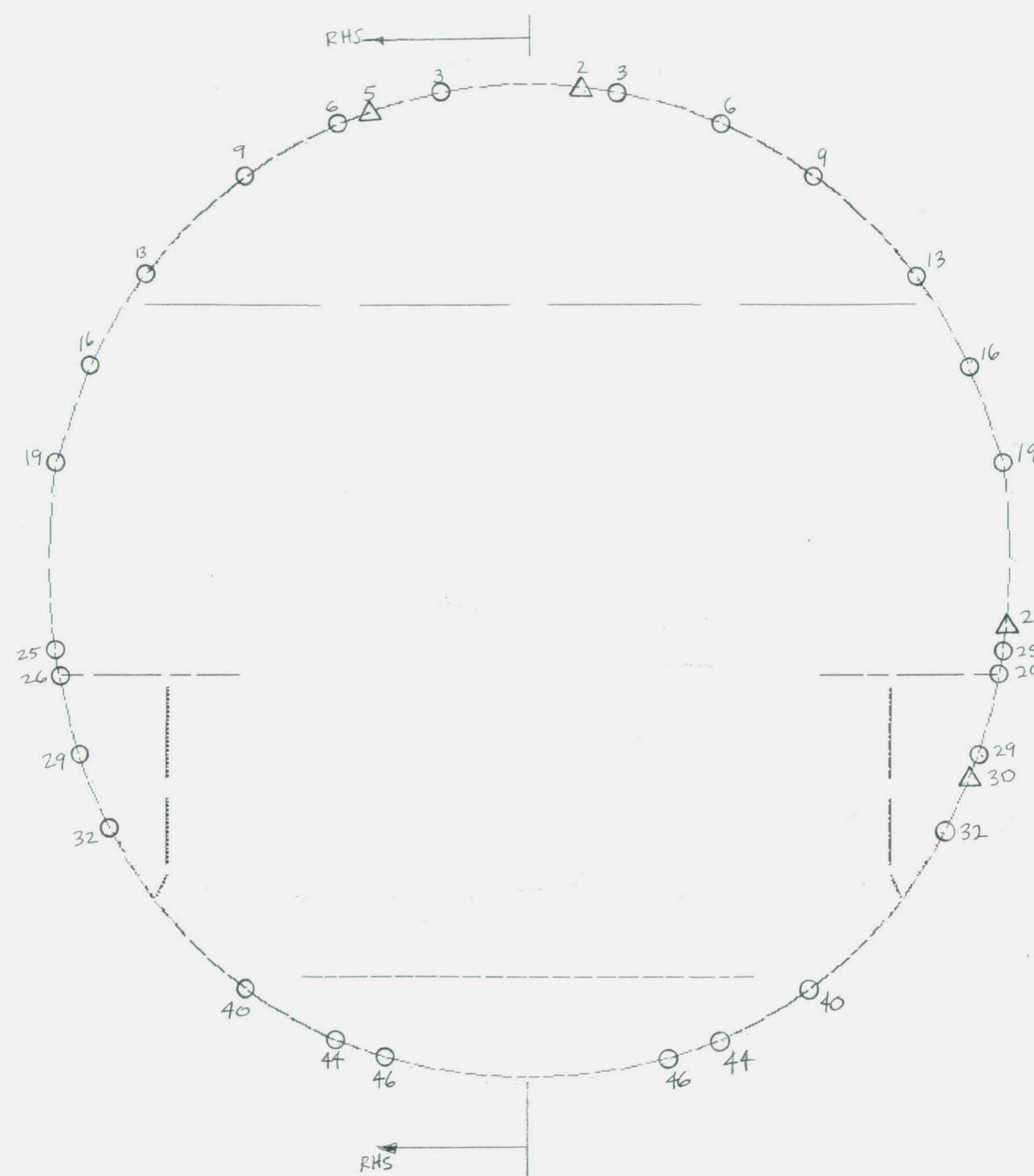
PLANE 1 MOMENT
(IN-LBS)

220000
66667
-66667
-220000

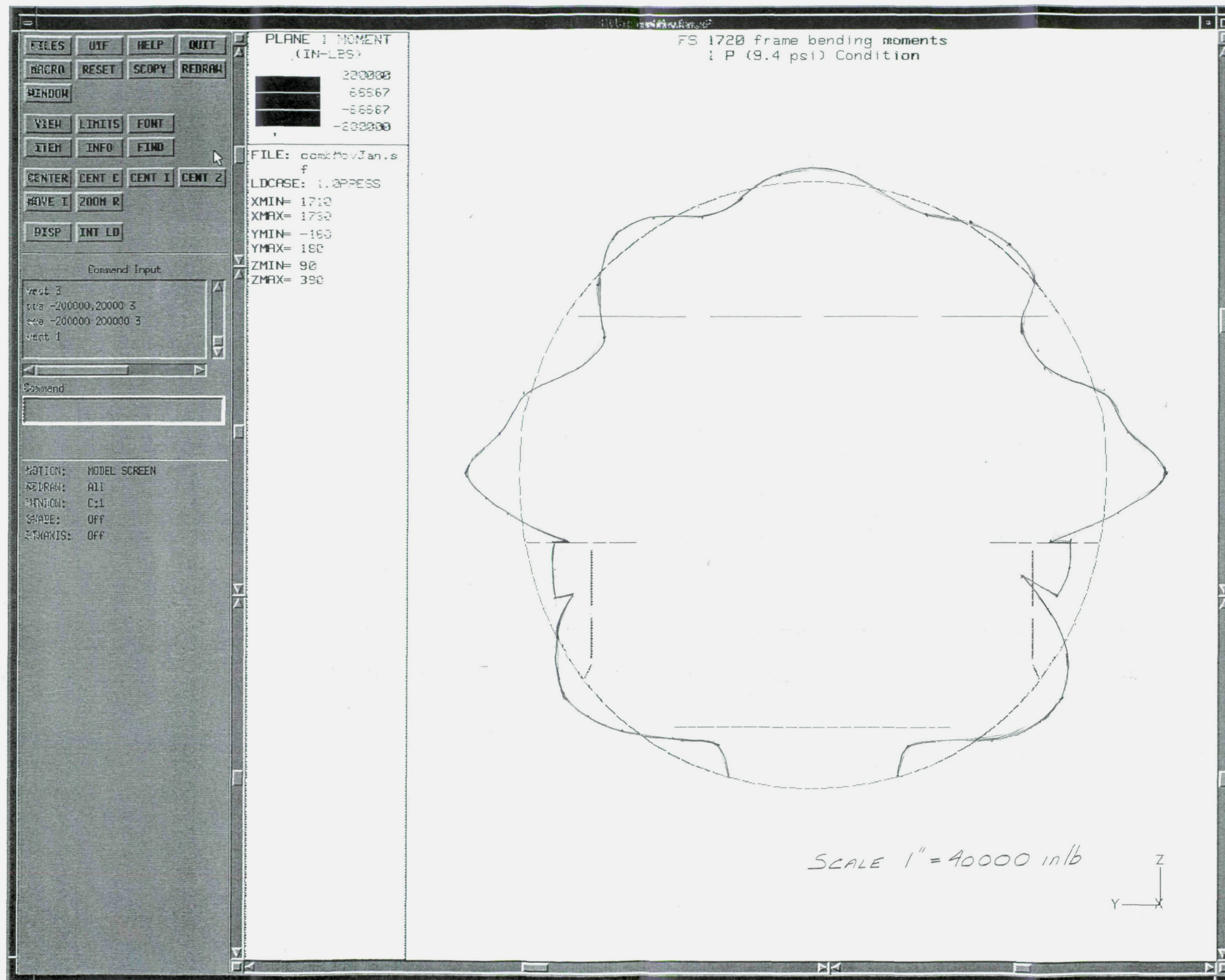
FILE: combtoVJan.s
f
LDCASE: 1.2PRESS
XMIN= 1710
XMAX= 1730
YMIN= -180
YMAX= 180
ZMIN= 90
ZMAX= 390

FS 1720 frame bending moments
: P (9.4 psi) Condition

TRANSITION JOINT MEMBER LOCATIONS ○
CUTOUT LONGITUDINAL LOCATIONS △



Z
Y
X



FILES UIF HELP QUIT
 MACRO RESET SCOPY REDRAW
 WINDOW
 VIEW LIMITS FONT
 ITEM INFO FIND
 CENTER CENT C CENT I CENT Z
 MOVE I ZOOM R
 DISP INT LD

ELEMENT TYPES
 BEAM
 ROD
 RIGID
 SHEAR
 SHELL
 FILE: joiIntegCs_0
 4.sf
 LDCASE: Fvalve
 XMIN= 1680
 XMAX= 1740
 YMIN= 74
 YMAX= 75
 ZMIN= 90
 ZMAX= 120

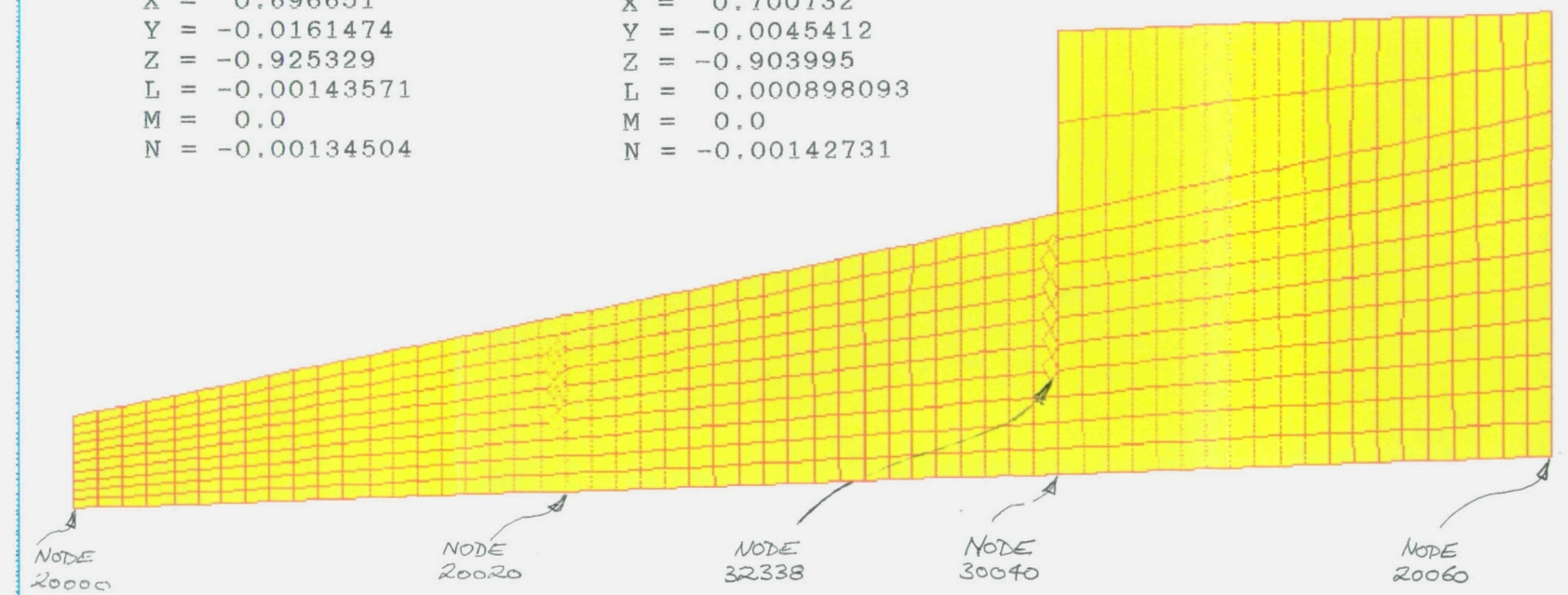
Command Input
 Command

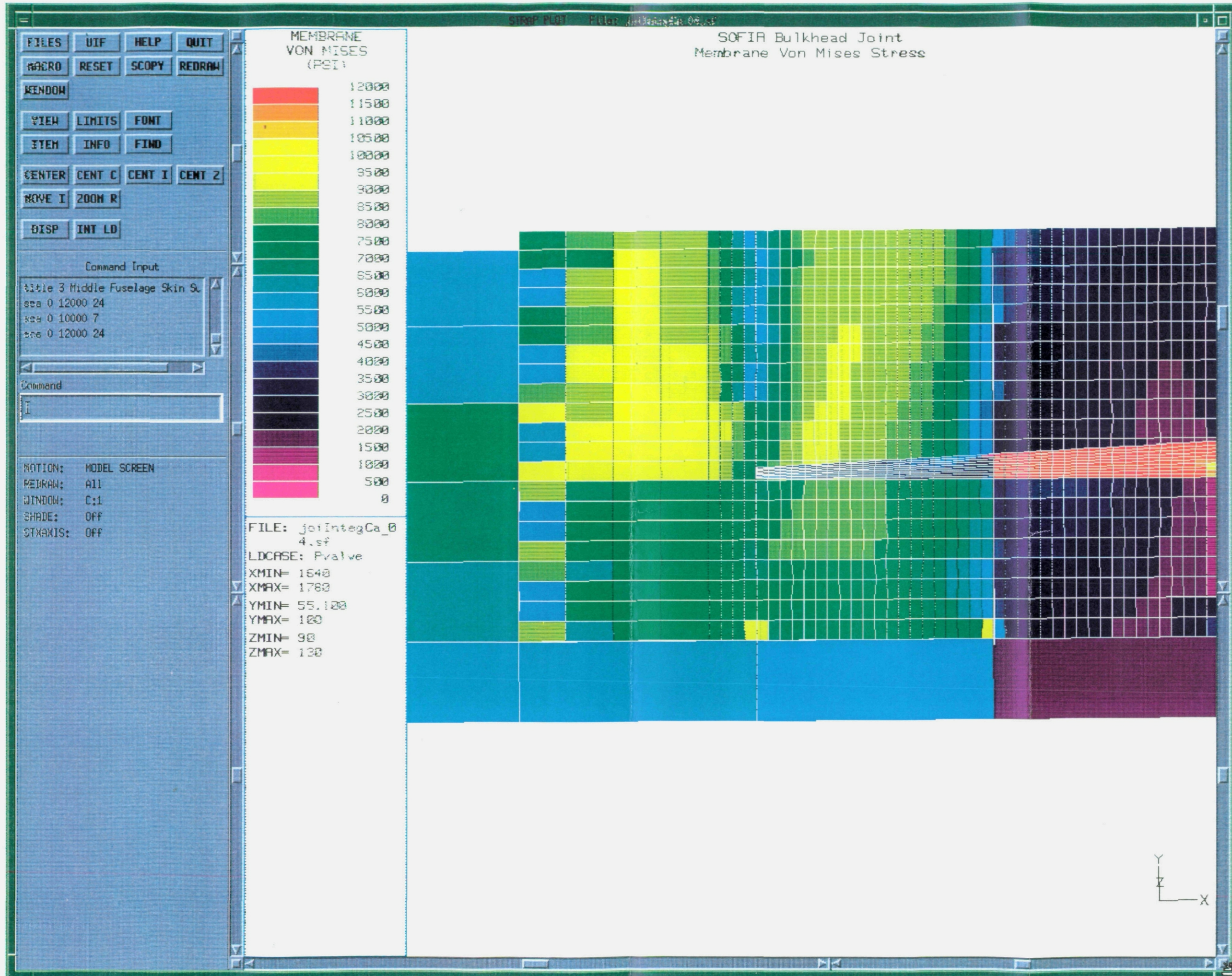
MOTION: MODEL SCREEN
 REDRAW: All
 WINDOW: C:1
 SHADE: Off
 STXAXIS: Off

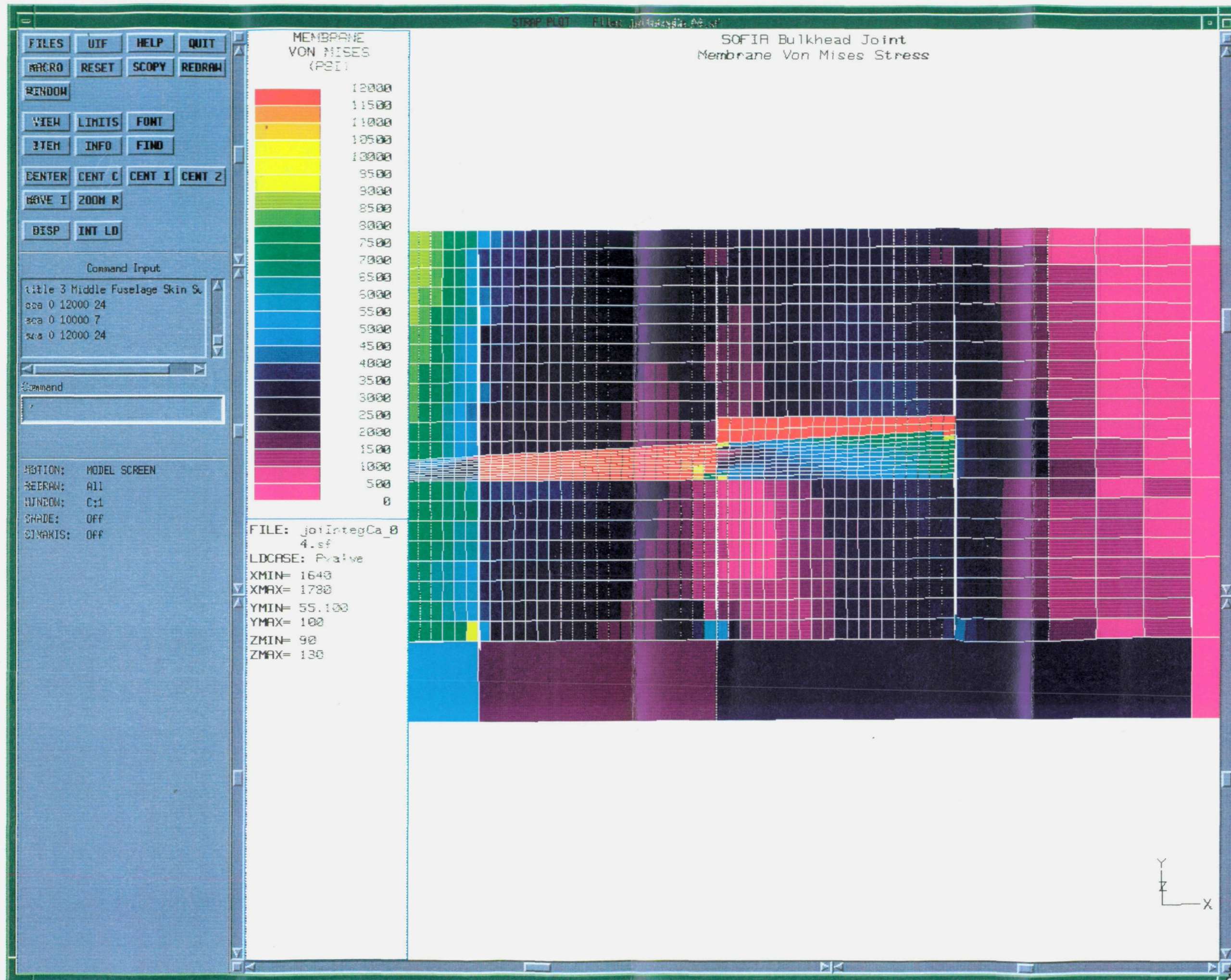
DISPLACEMENTS - TRANSITION INTERCOSTAL

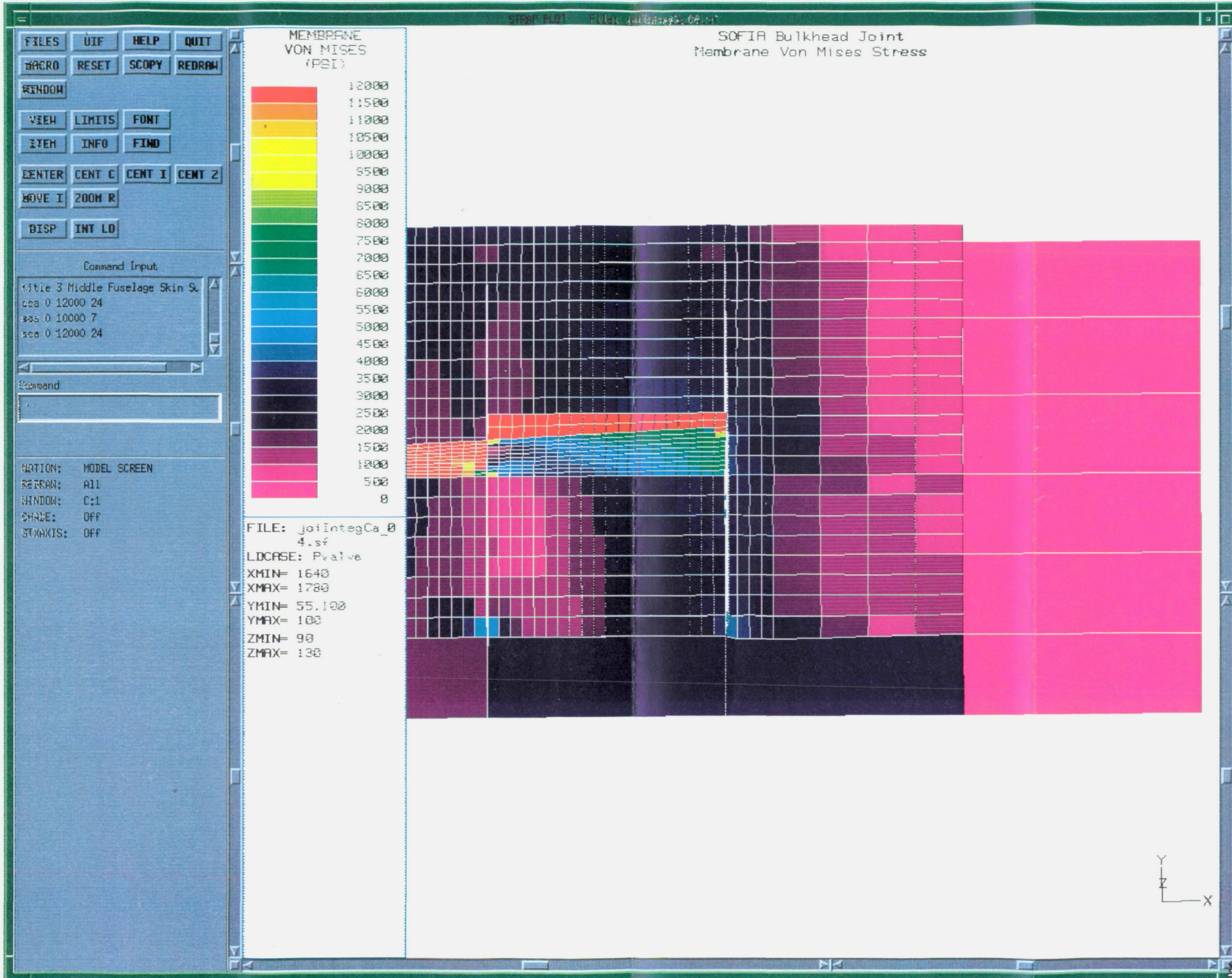
Grid 20060	Grid 30040	Grid 32338
Displacements :	Displacements :	Displacements:
X = 0.702151	X = 0.702246	X = 0.71251
Y = 0.211019	Y = -0.0132211	Y = -0.0072274
Z = -0.984673	Z = -0.907433	Z = -0.905193
L = 0.000162436	L = -0.0027234	L = -0.00197645
M = 0.0	M = 0.0	M = 0.0
N = 0.00166953	N = 0.000745929	N = 0.000438332

Grid 20000	Grid 20020
Displacements :	Displacements :
X = 0.696651	X = 0.700732
Y = -0.0161474	Y = -0.0045412
Z = -0.925329	Z = -0.903995
L = -0.00143571	L = 0.000898093
M = 0.0	M = 0.0
N = -0.00134504	N = -0.00142731





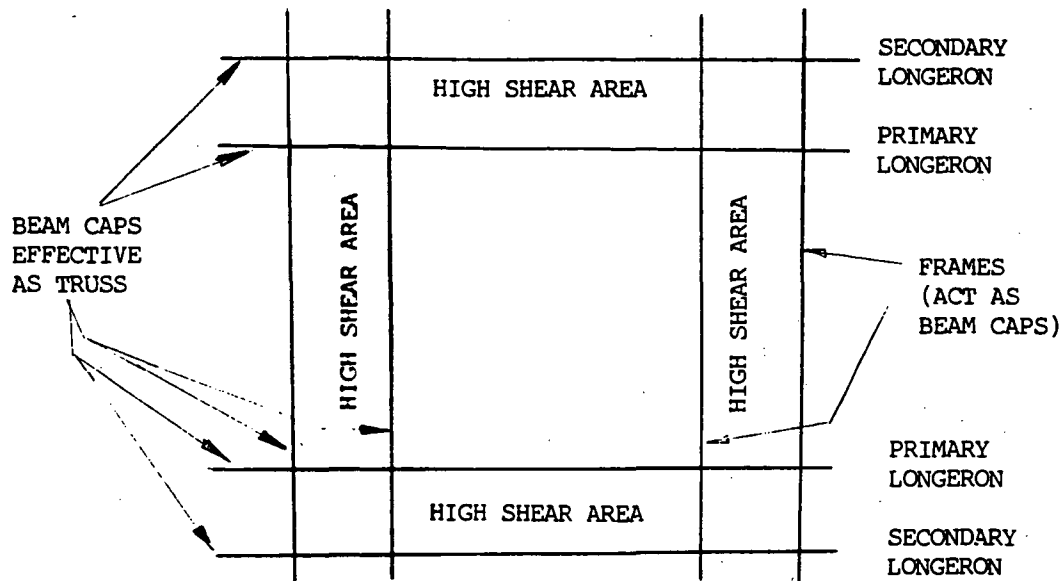




4.0 STRUCTURAL DESCRIPTION AND ANALYSIS RESULTS (cont'd)

4.4 CUTOUT SURROUND STRUCTURE

The purpose of the cutout surround structure is to frame the cutout opening and restore the aft fuselage strength and stiffness lost due to the shell cutout. It does this by essentially acting as a Vierendel Truss using the primary and secondary frames and longerons to form I beams framing the cutout. This is shown on sheet 6 of drawing B45114000 and depicted schematically below.



To permit operation of the cavity door the primary longerons (the ones immediately adjacent to the opening) are external to the shell mold line and faired with a fiberglass fairing for aerodynamic smoothness. The secondary longerons are internal. The skin between the primary and secondary members is doubled up to carry the high shear loads and a tripler is added to provide extra reinforcement to the skin immediately adjacent to the cutout. The longerons carry high axial loads and are unsupported columns between the bulkheads, a distance of 180 inches, and hence require large moments of inertia.

Upper Primary Longerons required Moment of Inertia = 100 in⁴

Upper Secondary Longerons required Moment of Inertia = 35 in⁴

Lower Primary Longerons required Moment of Inertia = 70 in⁴

Upper Secondary Longerons required Moment of Inertia = 50 in⁴

All Longerons are assigned a cross-sectional area of 6 in² for this study.

4.0 STRUCTURAL DESCRIPTION AND ANALYSIS RESULTS (cont'd)
4.4 CUTOUT SURROUND STRUCTURE (cont'd)

The longerons are of conventional construction with extruded or machined caps and a stiffened shear web between them. Where the caps must be spliced, to go through a bulkhead or frame, or to transition down to a reduced height, machined fittings are used.

The stringers are spliced with fittings similar to the standard Boeing stringer splices where they pass through the two bulkheads. The basic difference is a flat web machined into the fitting. This web attaches to the bulkhead cap ring on the side opposite to the cavity. The flange prevents pressure leaks from the cabin into cavity where the fitting passes through the mousehole in the cap. A typical fitting is shown on sheet 8 of drawing B54114000.

The cutout surround doubler at the forward bulkhead extends around the full circumference of the aircraft to form part of the bulkhead to shell interface described in section 4.3. The doubler also extends along the line of the longerons and cutout surround frames to aid in load runout.

The tripler is of limited extent and made from segments of 2024 plate, machine spliced together and tapered at the ends to aid in the longeron load runout redistribution. At the forward end of the cutout, the tripler extends from the cutout edge to the forward bulkhead cap. This provides added support and stability to the overhanging skin and door track frame.

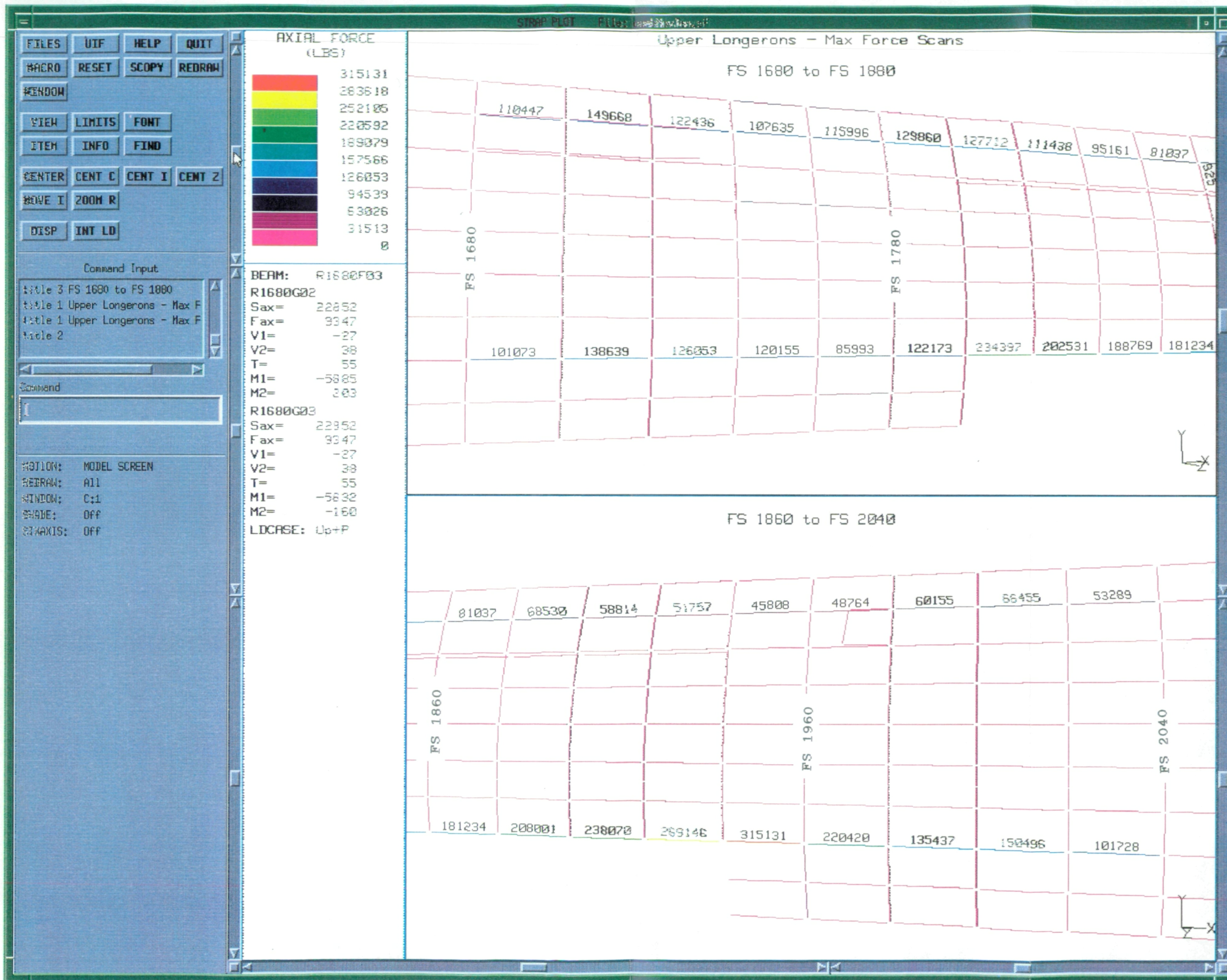
The preferred materials for the cutout surround structure are:

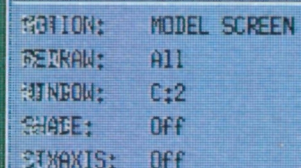
Longeron caps	7075-T76 extrusion
Stringer splices	7075-T73 hand forged billet
Doubler	2024-T3 Clad
Tripler	2024-T861 Plate
Longeron Splice Fittings	7075-T73 bar

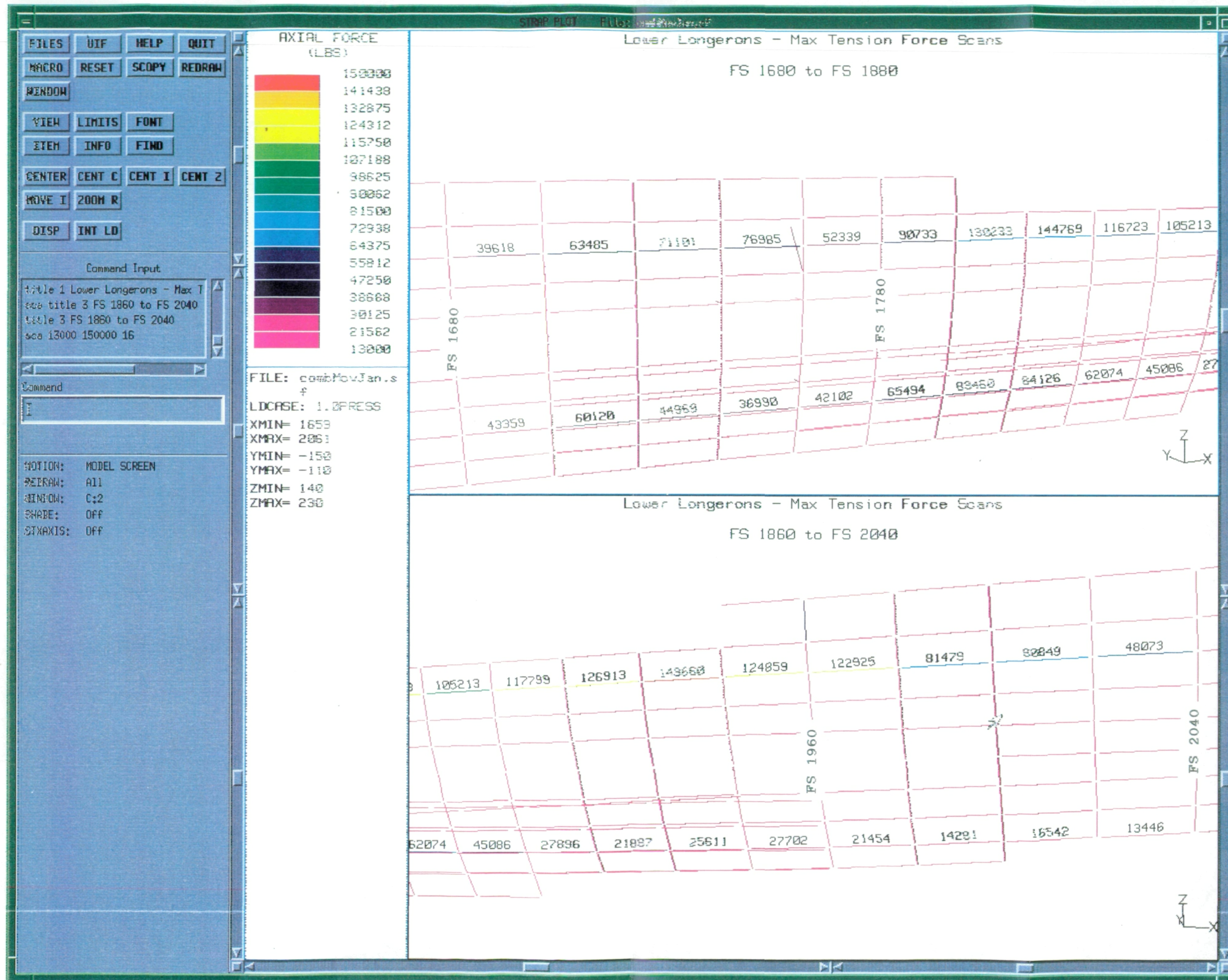
4.0 STRUCTURAL DESCRIPTION AND ANALYSIS RESULTS (cont'd)
4.4 CUTOUT SURROUND STRUCTURE (cont'd)

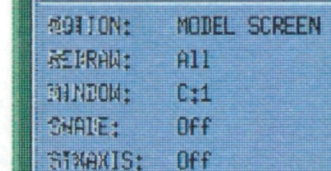
The results of the FEA runs are summarized on the following pages as shown on the chart below.

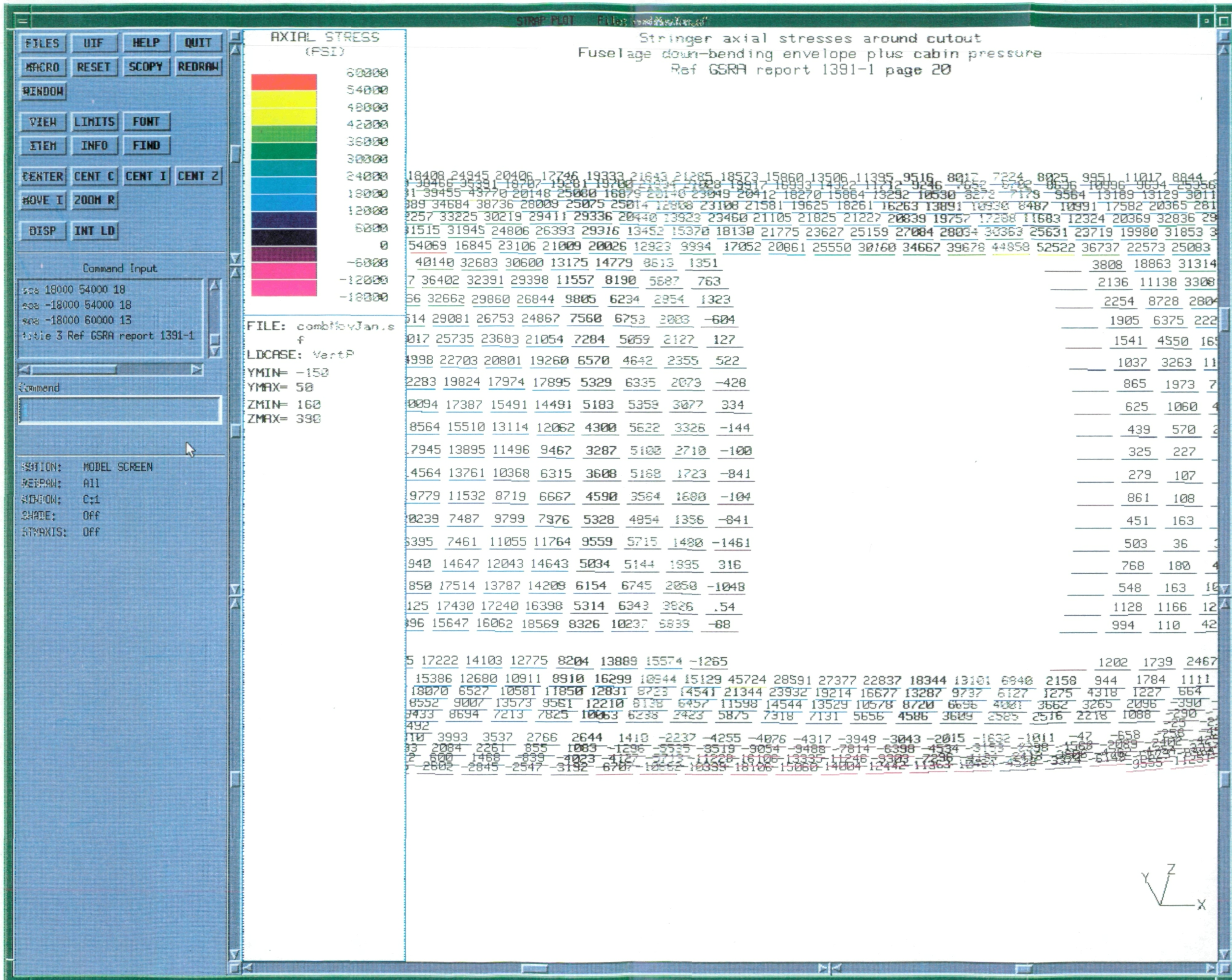
Page	Description
4.43	Upper Longerons Axial Load - Max Tension Load Scans
4.44	Upper Longerons Axial Load - Max Compression Load Scans
4.45	Lower Longerons Axial Load - Max Tension Load Scans
4.46	Lower Longerons Axial Load - Max Compression Load Scans
4.47	Stringer Axial Stresses around Cutout - Fuselage Downbending Envelope plus Cabin Pressure
4.48	Stringer Axial Stresses around Cutout - Fuselage Sidebending Envelope plus Cabin Pressure
4.49	Shell Axial Stresses around Cutout: Upper view Download Envelope plus Cabin Pressure Lower view Upload Envelope plus Cabin Pressure Left Side of Fuselage
4.50	Shell Axial Stresses around Cutout, Upper Fuselage: Upper View Side-load Envelope (right) plus Cabin Pressure Lower View Side-load Envelope (left) plus Cabin Pressure
4.51	Shell Shear Flows around Cutout - Side-load Envelope Condition
4.52	Shell Shear Stresses around Cutout - Side-load Envelope Condition



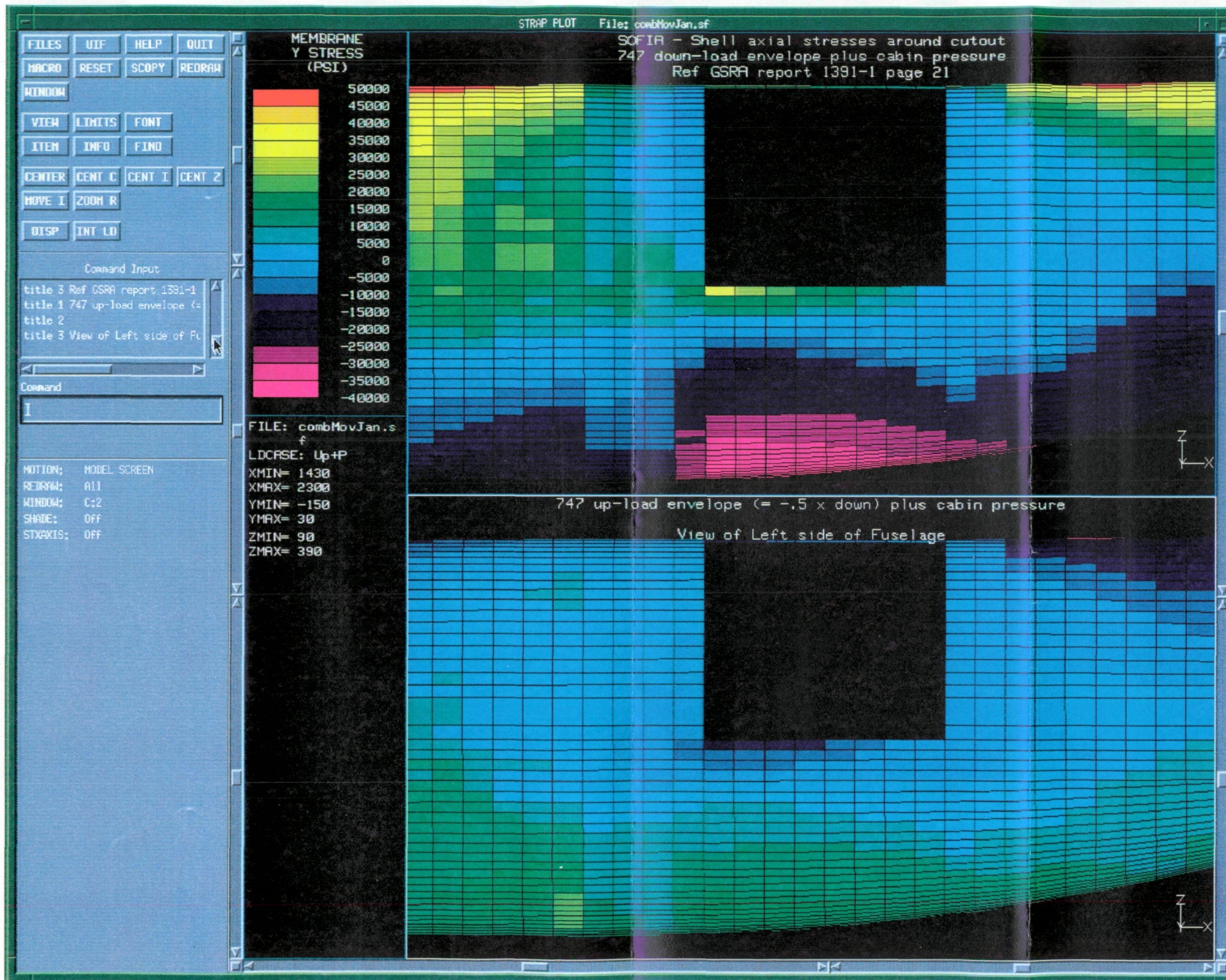


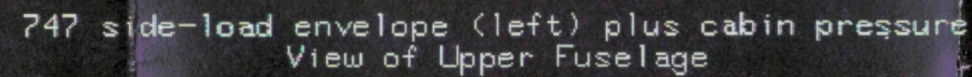


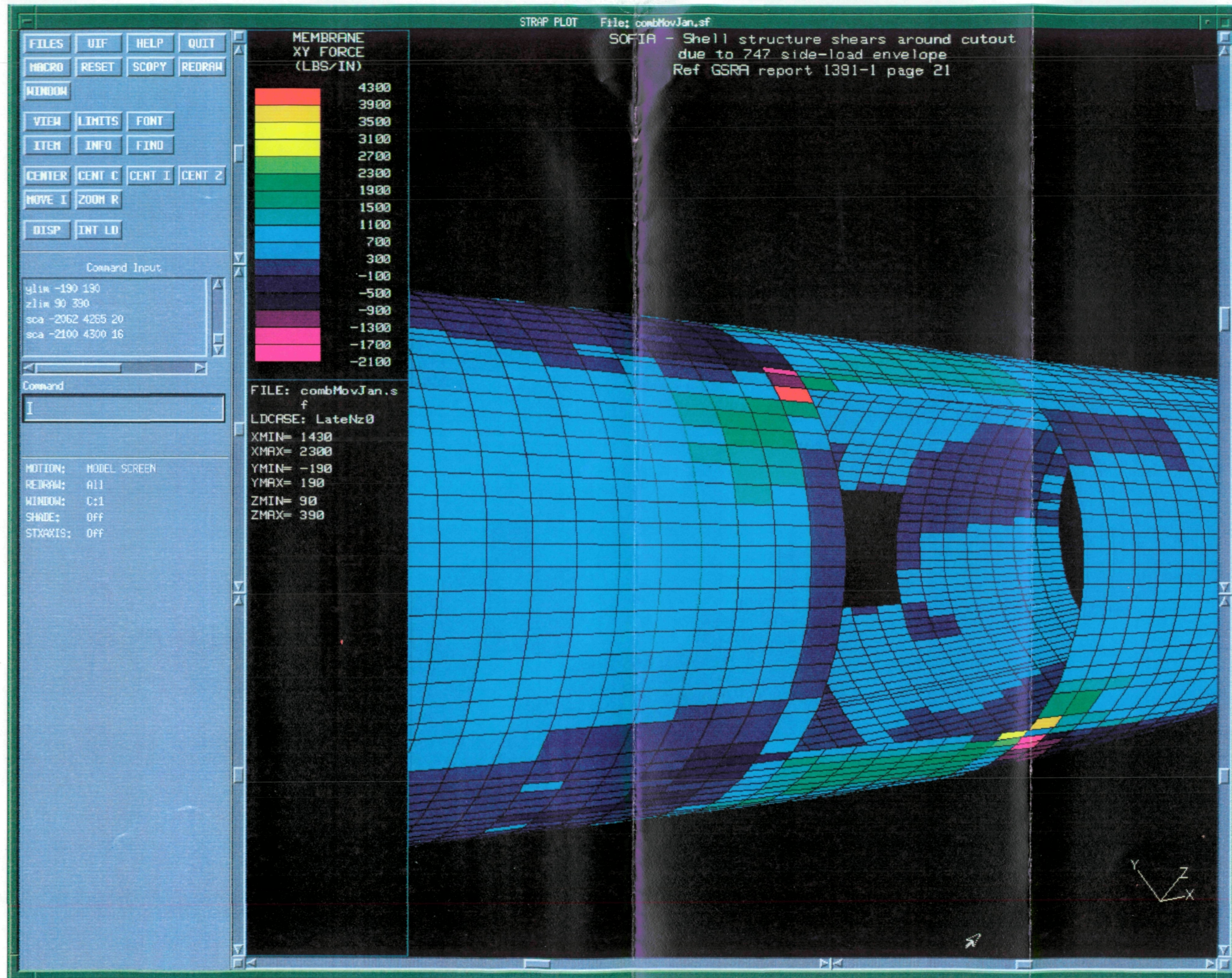


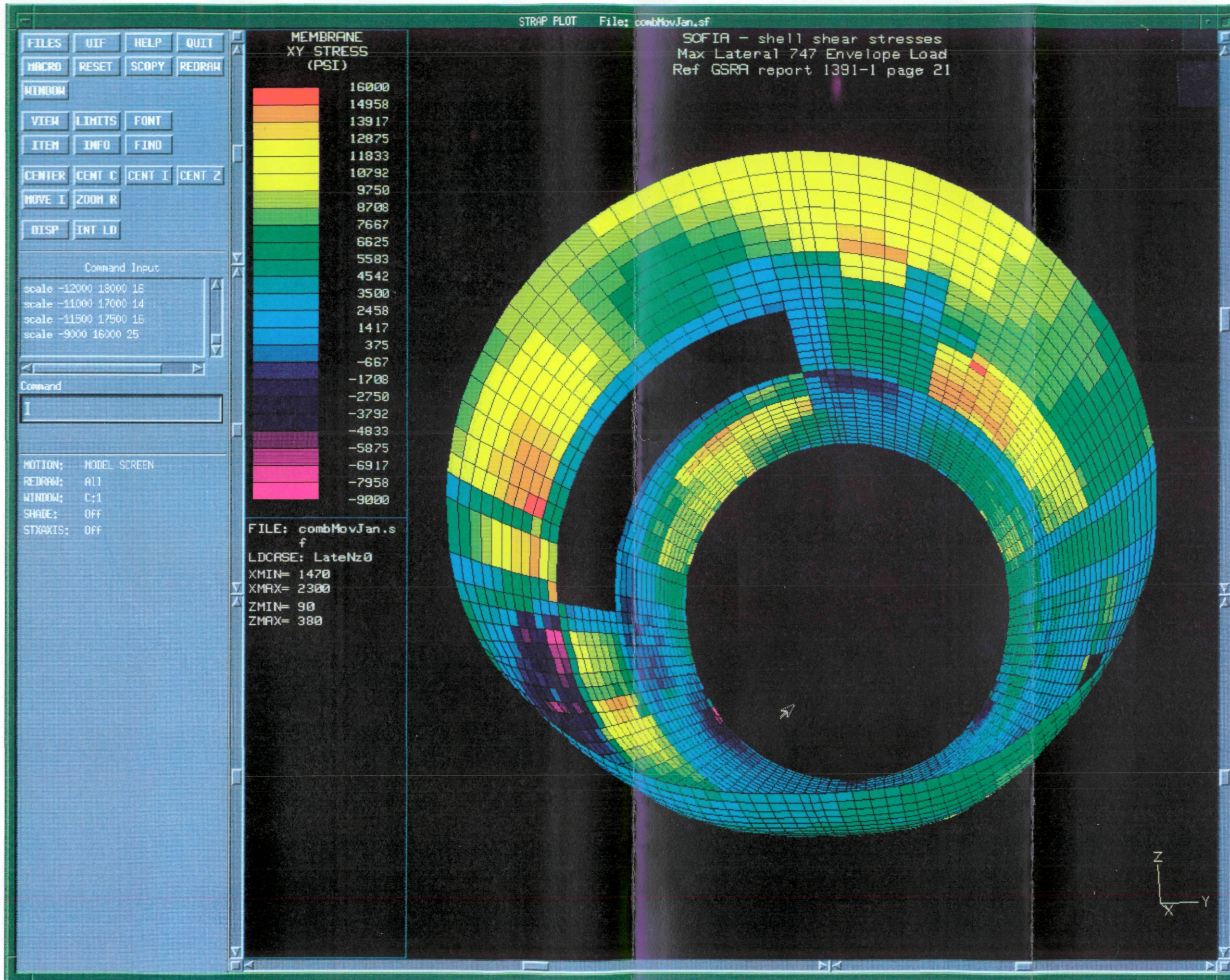










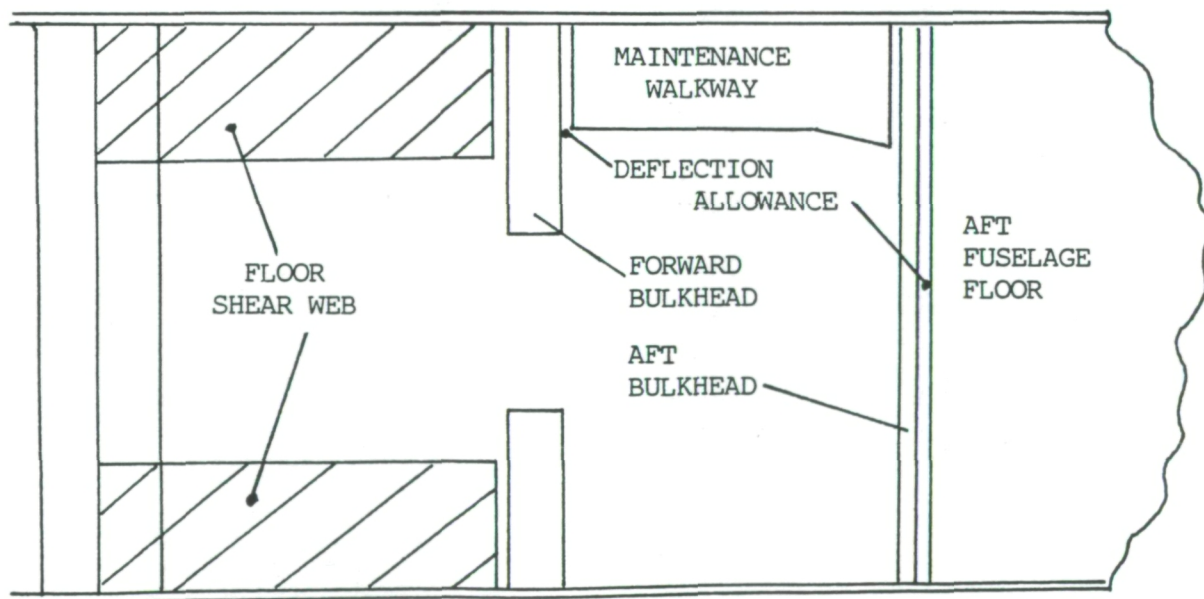


4.0 STRUCTURAL DESCRIPTION AND ANALYSIS RESULTS (cont'd)
4.4 FLOORING

With the exception of a maintenance walkway opposite the cavity opening, the main deck floor is removed between the cavity bulkheads to permit installation of the telescope. The floor is not attached to either bulkhead except at the skin line to permit the bulkheads to deflect freely under the various load conditions. The cargo floor is retained as is except for being cut back from the bulkheads, and a maintenance walking surface is added.

Forward of the pressure bulkhead and aft of FS 1600 the floor is cut away between BL 60L and 60R to permit installation of the telescope, and to provide comfortable access to the telescope instrument package.

The shell of the 747 is not circular: when the shell is pressurized it wants to achieve a circular cross-section to most efficiently react the loading. This is normally resisted by the maindeck floorbeams which are partially removed. To simulate this restraint the cut section of the floor has an inner cap and shear web added at WL 199.3 to force it to act as a deep beam supporting the shell between the bulkhead and FS 1580. As with other sections of floor adjacent to the bulkhead, the floor/beam is only attached to the bulkhead at the skinline.

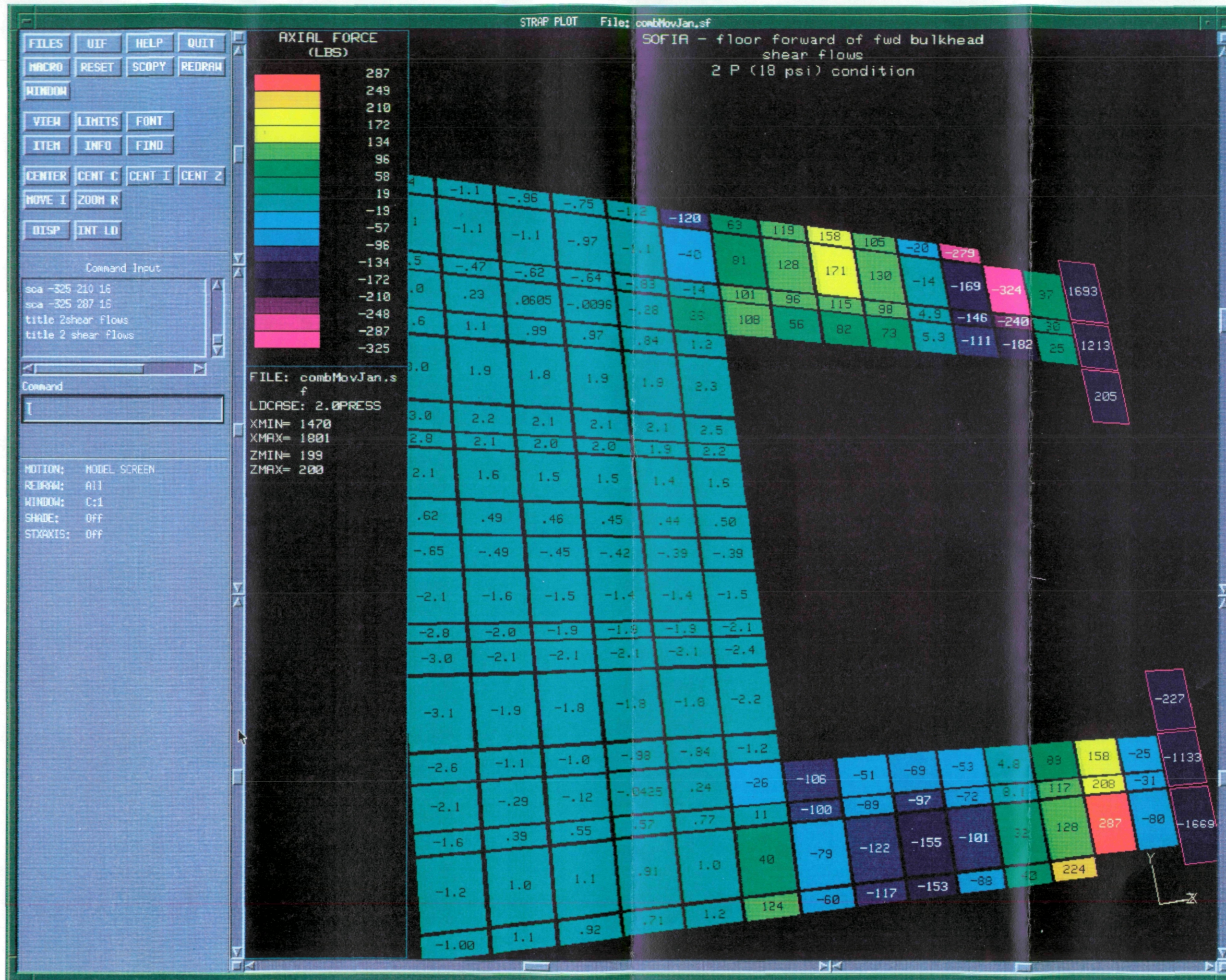


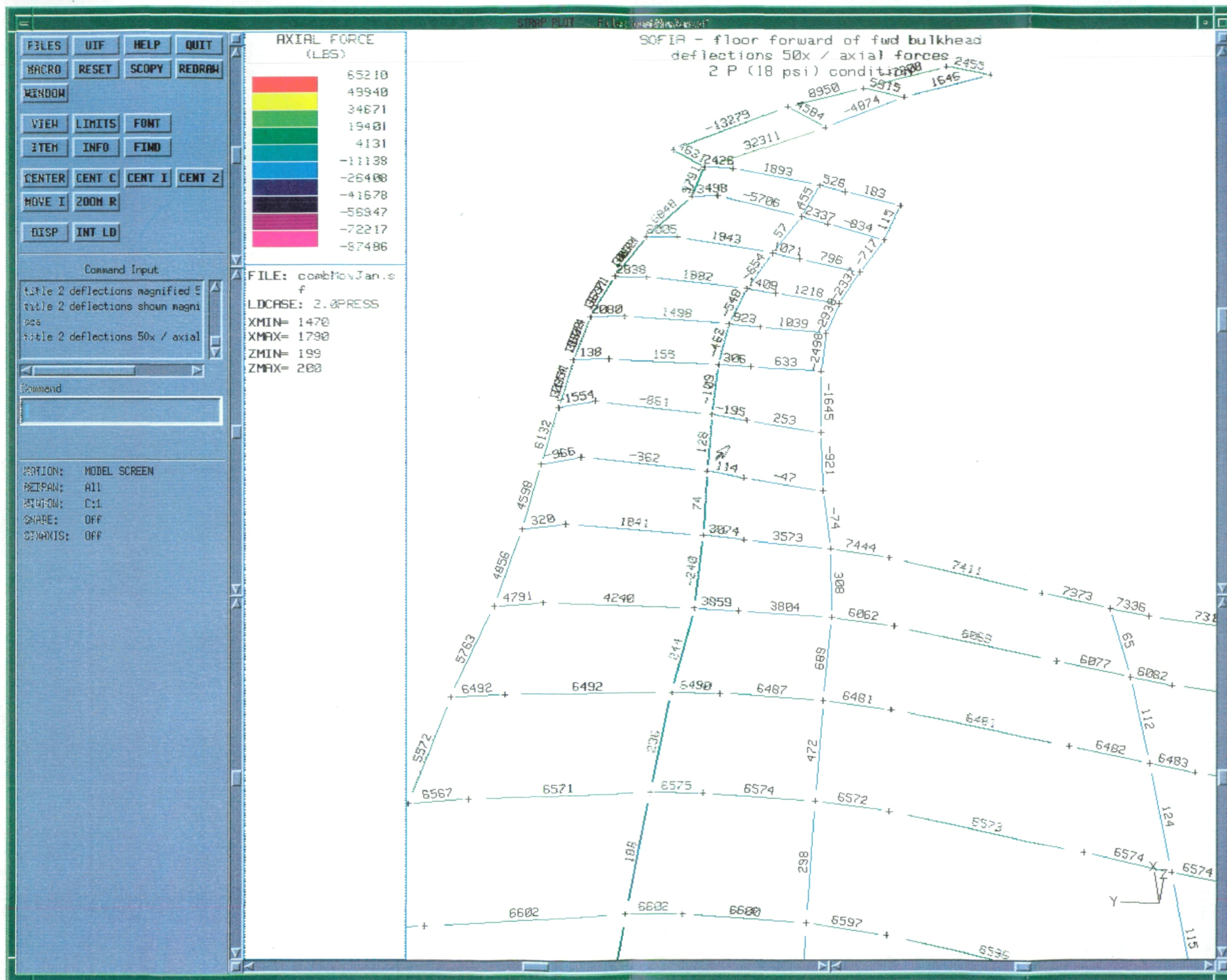
Floor Schematic
Ref Dwg B4511400 Sht 3

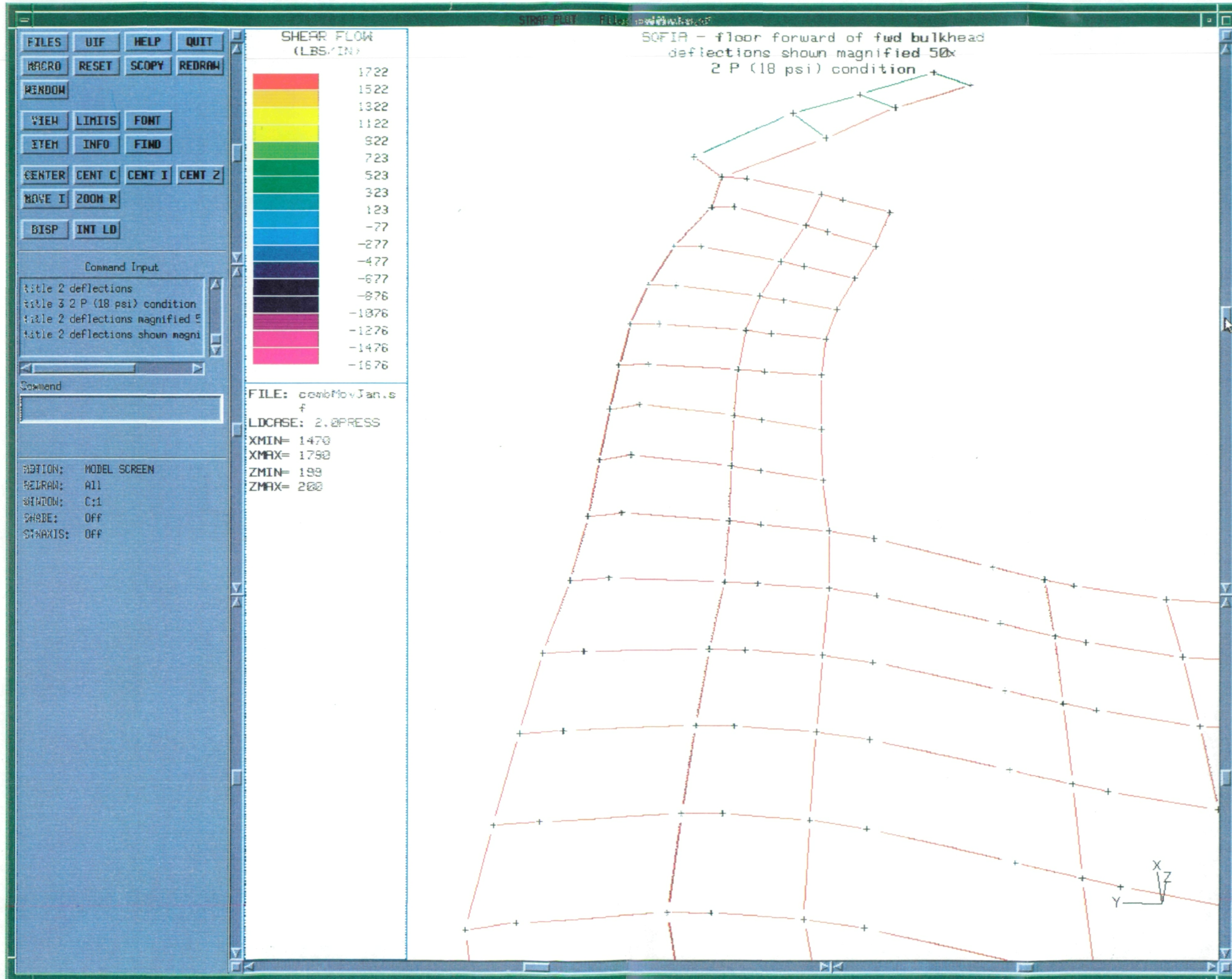
4.0 STRUCTURAL DESCRIPTION AND ANALYSIS RESULTS (cont'd)
4.4 FLOORING (cont'd)

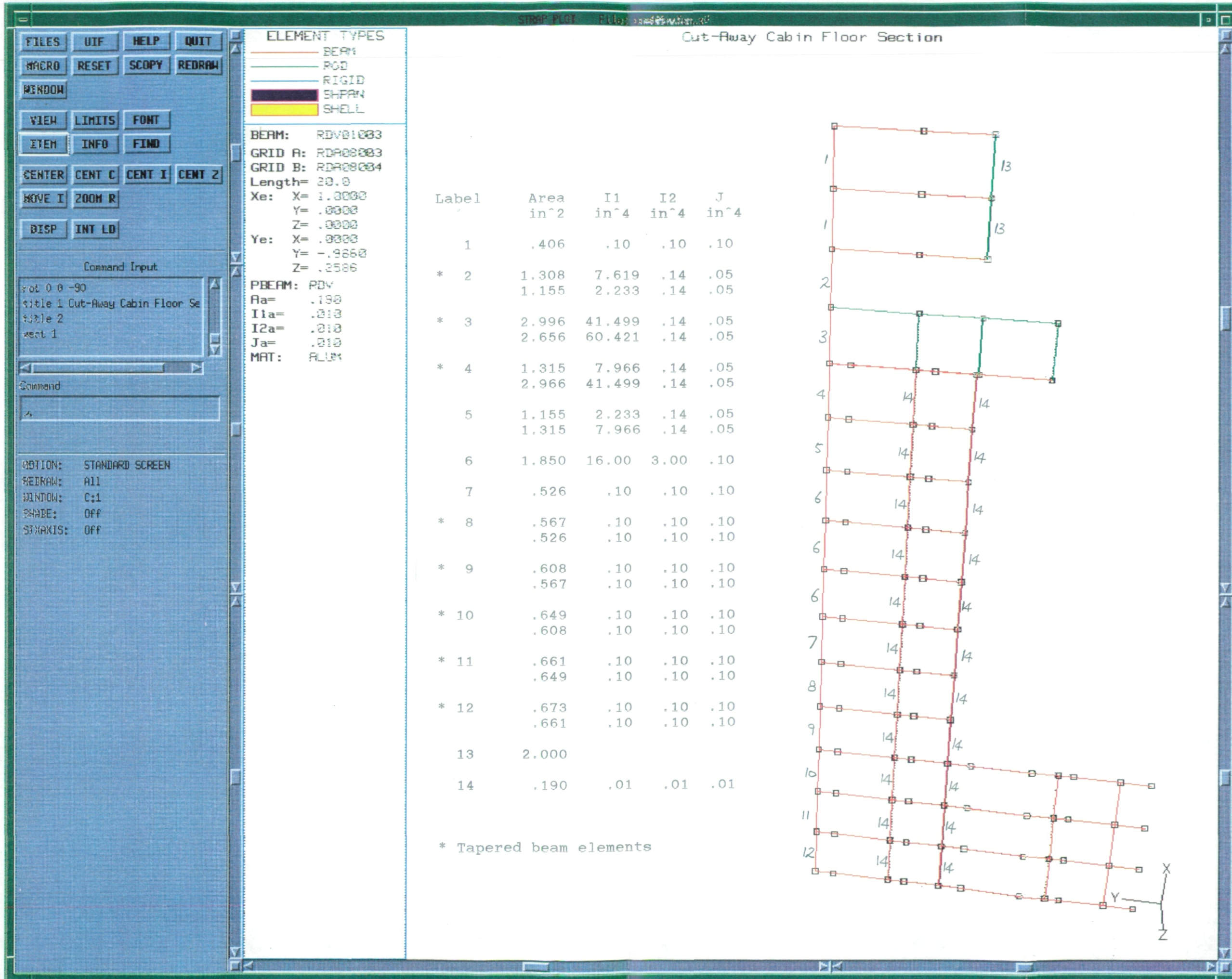
The results of the FEA runs are summarized on the following pages as shown on the chart below:

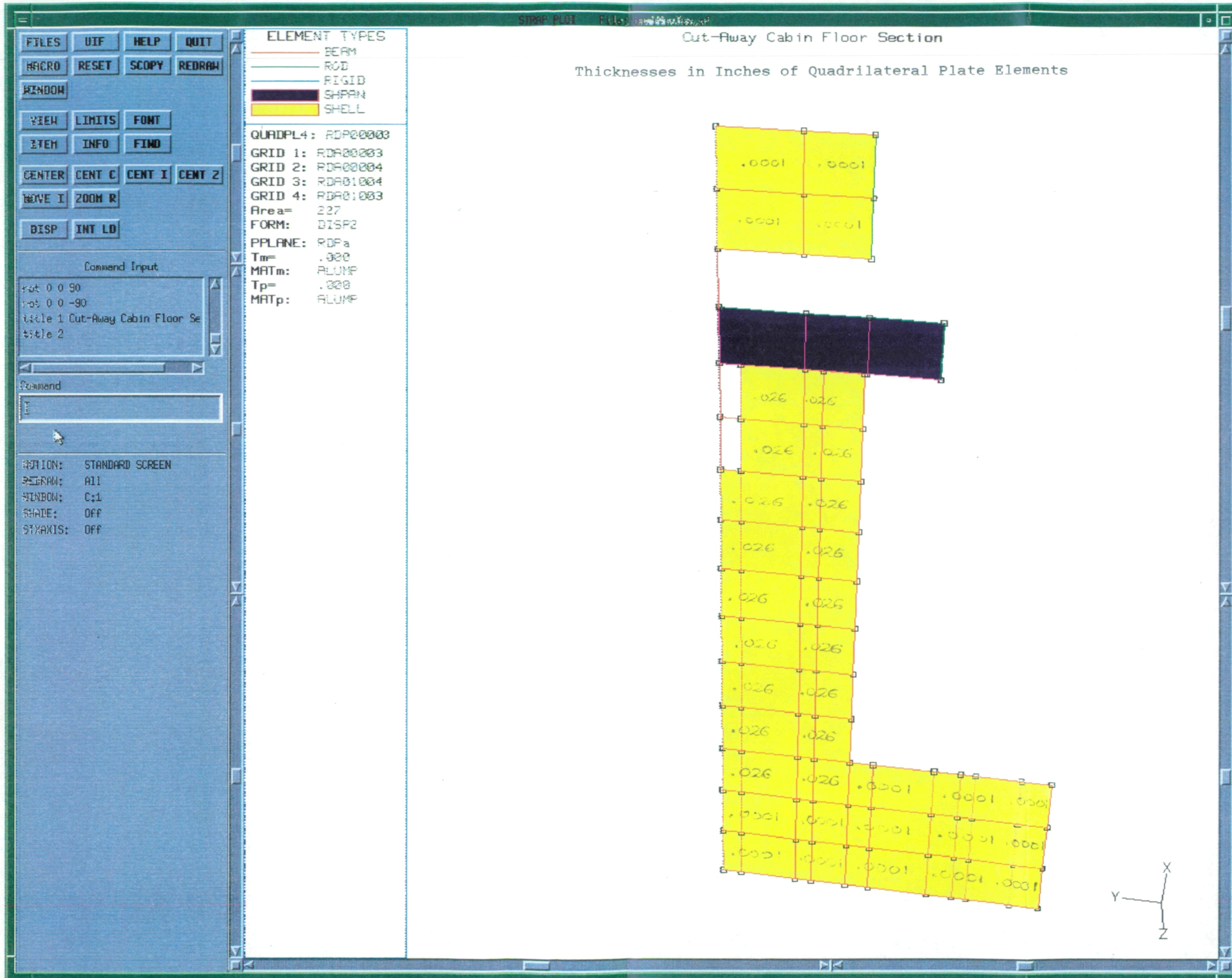
Page	Description
4.55	Main Deck Floor - Shear Flows at Added Shear Webs Condition - 2P (18.8 psi)
4.56	Main Deck Floor - Axial Forces in Members at Floor Cutout - Condition 2P (18.8 psi)
4.57	Main Deck Floor - Deflected shape of Floor Cutout Area - Condition 2p (18.8 psi)
4.58	Main Deck Floor Section Properties
4.59	Main Deck Floor - Added Shear Webs
4.60	Main Deck Floor - Bending Stresses and Displacements 9.4 psi cabin pressure

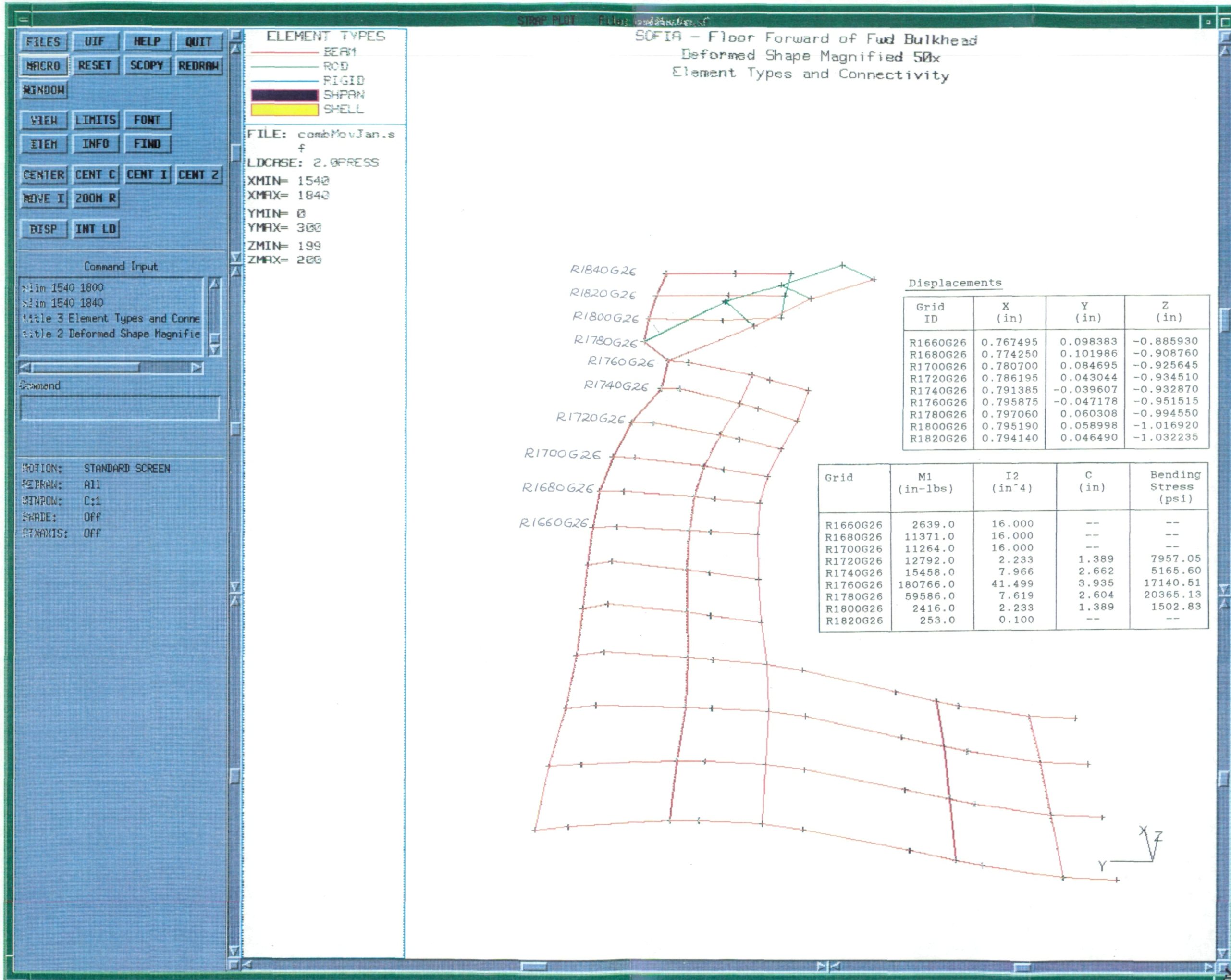












4.0 STRUCTURAL DESCRIPTION AND ANALYSIS RESULTS (cont'd)

4.6 STIFFNESS

4.6.1 Overall Airframe Stiffness

The relative stiffness of the baseline 747-100 and the 747 in the SOFIA configuration were compared by applying unit loads to the aft fuselage at FS 2180 with the fuselage being held fixed at FS 1480. The loads were applied to the shell through rigid elements which force the shell to hold its shape at the loaded end.

The results of this stiffness comparison are shown below:

Unit Load Type	SOFIA Stiffness/ Baseline Stiffness
Lateral Py	1.025
Vertical Pz	1.019
Torsion Mx	0.903

4.6.2 Bulkhead Stiffnesses

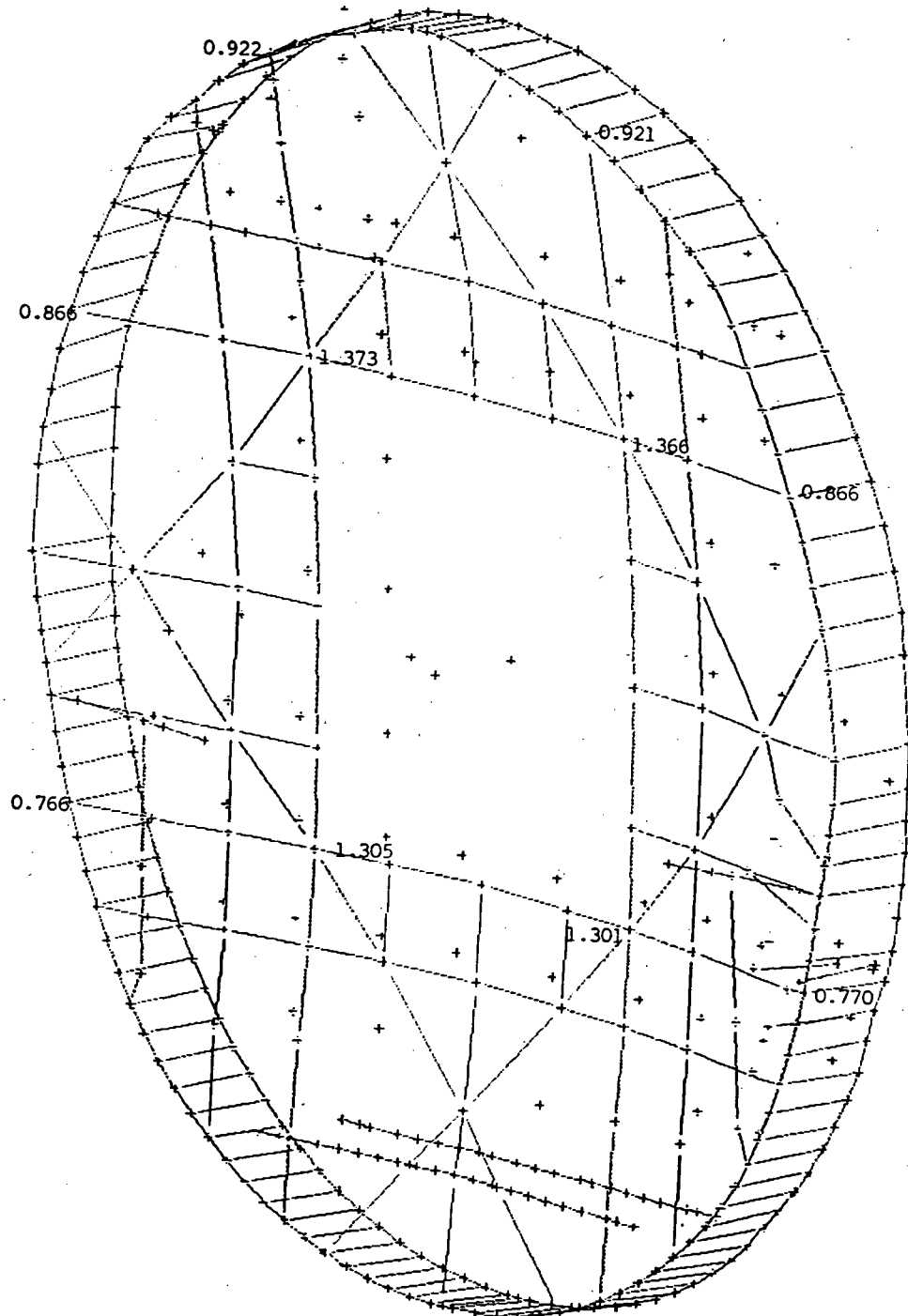
The deflection of the forward (pressure) bulkhead under 9.4 psi cabin pressure is shown on page 4.51. The deflections shown are relative to an unloaded airframe. The relevant deflections are those of the telescope attach points at the four corners to the shell. This deflection is 0.531 inch maximum at the lower right hand corner.

The deflection of the aft bulkhead is shown on page 4.52. The condition shown is for 9.4 psi cabin pressure and 5000 lb. limit brake load. The cabin pressure has no effect on the bulkhead directly but does serve to move the shell datum aft for comparison with the forward bulkhead deflection. No conditions were run with the bulkheads coupled through the brake spring as its characteristics are currently undefined.

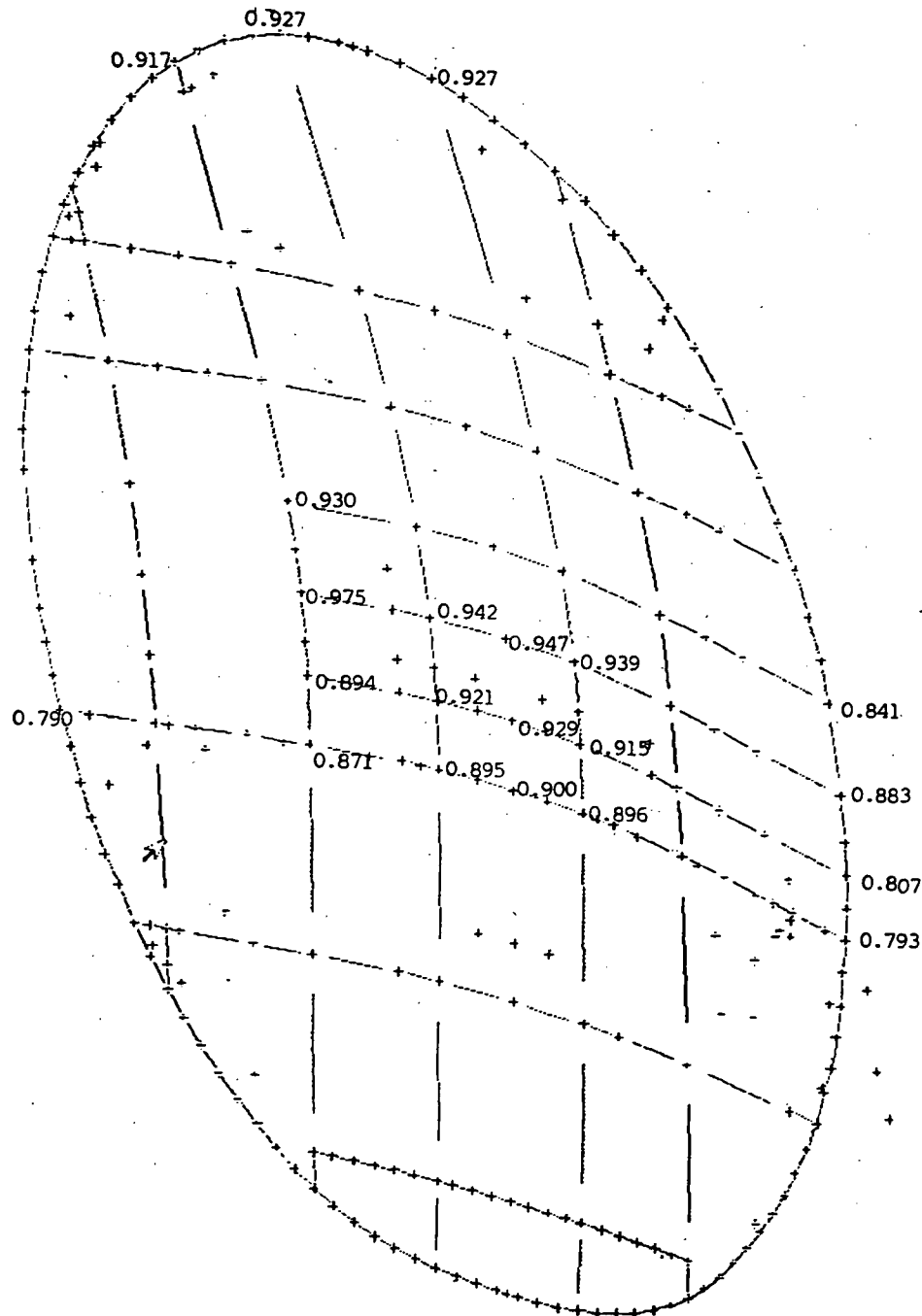
4.0 STRUCTURAL DESCRIPTION AND ANALYSIS RESULTS (cont'd)

4.6 STIFFNESS (cont'd)

4.6.2 Bulkhead Stiffnesses (cont'd)



Forward (Pressure) Bulkhead Deflections
9.4 psi Cabin Pressure



Aft Bulkhead Deflections
Condition 9.4 psi plus Brake Load

5.0 WEIGHT AND BALANCE
5.1 WEIGHT ESTIMATE

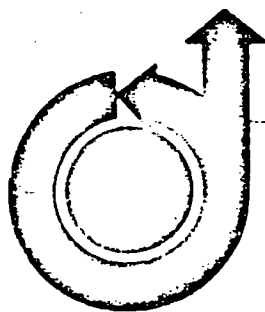
The weight of the SOFIA structure covered by this report, Forward Bulkhead, Aft Bulkhead, Bulkhead to Shell Interface, Cutout Surround Structure, and Flooring has been estimated using the FEA model with the weight change calculated for the before-mod and after-mod conditions. The structural weight estimate makes no allowance for Telescope local supports which are part of the Telescope/Bearing assembly nor does it reflect local structure required to support the Cavity Door, its associated mechanisms and equipment support.

Weight change of aluminum structure (from FEA model)
= + 7500 lb

Adding 35% for fasteners
and stiffeners, etc. = + 10125 lb
15% contingency = + 11640 lb

6.0 FUTURE TASKS

The cavity structure, bulkheads, surround structure, and bulkhead to shell transition should be investigated more deeply to validate the design concepts expounded here. This investigation should be down to the detail stress analysis level to ensure that design items accepted as feasible under the limited budget of this study can, in fact, be implemented.



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CORRELATION OF ANALYSIS AND TEST DATA TO THE
EFFECT OF FASTENER LOAD TRANSFER ON FATIGUE

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Marietta, Georgia

MICROFICHE AVAILABLE

**AIAA 6th Aircraft Design,
Flight Test
and Operations Meeting**

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CORRELATION OF ANALYSIS AND TEST DATA
TO THE EFFECT OF FASTENER LOAD TRANSFER ON FATIGUE

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Abstract

Presented is a Stress Severity Factor method of fatigue analysis for mechanically fastened, single shear aluminum lap joints, with one or two rows of titanium fasteners. Also presented is correlation of analysis predictions to test data from two full scale wing fatigue test articles representing the C-5A transport. Fatigue damage is calculated for each loading condition recognizing that the stress severity factor varies within each load cycle; considering parameters of fastener load, uniaxial stress, diameter to thickness ratio, fastener head configuration; and using joint S-N data which reflects fretting. Damage is summed for a spectrum using Palmgren-Miner's theory.

1.0 Introduction

The significance of load transfer in mechanically fastened structural joints has been increased in recent years by the development of high strength fastener systems in the 160-200 ksi UTS range. This development has tended to make structural joints more efficient statically, but not more efficient in fatigue. The design dilemma of creating a balanced structural joint, which satisfies both the static and fatigue criteria, is the establishment of the design hole bearing stresses. With strict design weight controls and the availability of high strength fasteners, it is natural for the designer to want to exploit the full fastener strength capability, thereby introducing high hole bearing stresses which may have an adverse effect in fatigue. To provide a technical basis to determine the design hole bearing stresses requires a fatigue analysis method which recognizes the effects of fastener load transfer. With such a method the structural joint can be designed for fatigue, and with the well established static methods of analysis, a balanced joint design can be obtained.

This paper will address the effects of fastener load transfer on the fatigue behavior of a single lap shear joint. A fatigue analysis method is presented and the results compared to existing methods of analysis using the test data obtained from two full scale fatigue test articles.

2.0 Fatigue Analysis Method

In a practical fatigue analysis method, for any type of mechanically fastener joint, it is advantageous to use existing technology as much as possible. The fatigue analysis method presented for single aluminum lap shear joints is, therefore, based on the conventional K_T -method of analysis. The readily available empirical constant amplitude notched S-N data are utilized, but are modified to joint S-N data by accounting for hole fretting effects. For joint damage calculations the well-known Palmgren/Miner's linear cumulative damage

theory is used.

Damage Equation

The Palmgren/Miner's equation can be expressed as follows:

$$D_T = \sum_{m=1}^{m=L} \frac{n_m}{N_m} = \frac{n_1}{N_1} + \frac{n_2}{N_2} + \dots + \frac{n_{m=L}}{N_{m=L}}$$

Where

D_T = Total Damage, failure occurring when $D_T = 1$

n_m = Applied cycles at stress level m

N_m = Allowable cycles at stress level m

In this equation the value N_m is obtained from the S-N data and is a function of the uniaxial stress cycle and the associated joint stress concentration factor (K_T). Since the uniaxial stresses and number of applied cycles (n_m) are always known, the solution for the total damage depends on the determination of the K_T values.

In the past the K_T present in a joint has, in general, been determined experimentally. Jarfall⁽¹⁾ however, investigated the problem of analytically defining the significant parameters affecting the stress concentration factor in a lap axial joint, and proposed the "Stress Severity Factor (SSF) Method". Since SSF can be equated to K_T , the SSF Method is used to determine the joint K_T . The K_T -Method of fatigue analysis is, therefore, redefined and called the SSF-Method of fatigue analysis.

Stress Severity Factor Equations (SSF)

The basic equation for the SSF proposed by Jarfall for a lap axial joint is as follows:

$$\text{SSF (Lap Axial)} = \frac{\alpha \beta}{f_{\text{ref}}} \left[K_{TG} f_{bp} + K_{TB} \theta f_{br} \right]$$

Where f_{ref} = Gross area uniaxial reference stress away from joint (psi)

f_{bp} = Gross area uniaxial hole by-pass stress (psi)

f_{br} = Uniform hole bearing stress (psi)

K_{TG} = Gross area uniaxial stress concentration factor

K_{TB} = Hole bearing stress concentration factor

θ = Fastener tilt factor, ratio of uniform to peak hole bearing stress

* Aircraft Development
Engineer Specialists

α β = Empirical hole preparation and hole filling factors, respectively

Unfortunately, this SSF equation, in its present form, cannot be used for a lap shear joint as the load path of the transfer load is different. Figure 1.0 compares the load transfer characteristic of the lap axial and lap shear joints. It can be seen that, in the lap axial joint the load transfer produces a uniaxial stress gradient across the joint with no shear stress gradient, while in the lap shear joint the exact opposite is true. The load transfer in the lap shear joint produces a shear stress gradient across the joint and no uniaxial stress gradient.

To account for these affects, and make the SSF equation applicable to a lap shear joint, the basic SSF equation is modified and expanded into the form:

$$\text{SSF (Lap Shear)} = \frac{\alpha \beta}{f_{ax}} \left[K_{TG} f_{ax} + K_{TB} \theta f_{br} + K_{TS} \tau \right]$$

Where f_{ax} = Gross area uniaxial stress acting along the joint (psi)

τ = Gross area shear stress away from joint (psi)

K_{TS} = Gross area shear stress concentration factor compatible with K_{TG} and K_{TB}

The remaining terms being as defined in the SSF equation for the lap axial joint.

In both the lap axial and lap shear SSF equations, the terms inside the brackets describe the magnitude of the peak stress in the joint material at the edge of the fastener hole. Figure 2.0 shows a pictorial breakdown of the peak stress into the three stress components present in the lap shear joint. The first and third terms are, simply, gross area stresses times a stress concentration factor and give the peak stress components due to the uniaxial and shear stresses, respectively. The second, or middle, term is similar, and gives the peak stress component due to the hole bearing stress. However, the term contains the fastener tilt factor (θ). By definition, θ is equal to the ratio of uniform to peak hole bearing stress, and is required to account for the peaking that occurs at the faying surface of the joint when the fastener deforms (tilts) under the action of the load transfer. The value of θ depends on whether the joint is of the single or double shear type. An approximate analytical solution for θ , in a single aluminum lap shear joint, is presented in Section 4.0. Curves of θ versus t/D for two thickness ratios using titanium fasteners are also presented in this section. To derive values for the stress concentration factors K_{TG} , K_{TB} , and K_{TS} a typical single lap shear joint with two rows of fasteners is analyzed using finite element techniques. A discussion of this analysis and final values for the stress concentration factors are presented in Section 3.0.

To account for hole preparation and hole filling effects the peak stress is corrected to an apparent peak stress by applying the α and β factors. These factors are empirical and must be determined by test. The finite element analysis of Section 3.0 uses the condition of a perfectly

finished hole and a neat fitting fastener as the baseline condition. A hole and fastener installation which meet these conditions could, therefore, be expected to demonstrate $\alpha = 1$ and $\beta = 1$. For holes that have a less than perfect finish the α factor should increase and for fasteners with interference or clamp-up the β factor should decrease. The approach used to determine the α and β factors on two full scale test articles is discussed in Section 5.0.

The final step in determining the SSF is to divide the product of α , β and the peak stress by the gross area uniaxial stress (f_{ax}). By performing this operation it is apparent that, if f_{ax} approached zero and the terms containing f_{br} and τ had some finite value, SSF would approach infinity. In a structure, such as a wing box, this condition could only be achieved if the wing is subjected to pure torsion. In a realistic loads environment a wing will never experience just pure torsion; some bending must always be present. Hence this extreme condition should never arise.

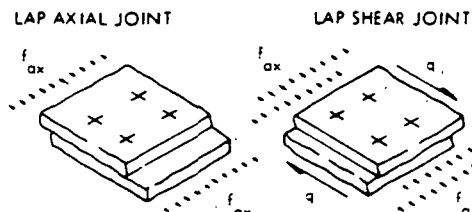


FIGURE 1.0 LOAD TRANSFER - LAP AXIAL AND LAP SHEAR JOINTS

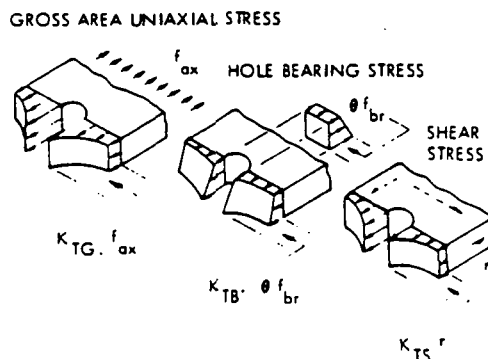


FIGURE 2.0 PEAK STRESS COMPONENTS - LAP SHEAR JOINT

Uniform Hole Bearing Stress (f_{br}) and Shear Stress (τ)

For a single lap shear joint, it is convenient to express the fatigue loads in terms of the gross area uniaxial stress and shear flow (q). Again, referring to Figure 1.0 which shows the load transfer characteristic of the lap shear joint, the fastener loads can be readily calculated using the equation:

$$\Delta P = a \cdot q / n$$

and therefore $f_{br} = \Delta P / D t$; $\tau = q / t$

Where

ΔP = Fastener Load (lbs)

a = Fastener pitch (ins)

n = Number of rows, 1 or 2 rows only

D = Fastener Diameter (ins)

t = Thickness of joint element to be analyzed (ins)

For the case $n = 2$ and unequal thickness elements, the fastener loads become statically indeterminate. However, providing the thickness ratio is not less than 0.7, analysis shows, the error in using the above equations is small.

Allowable Cycles (N)

Knowing the applied stress cycle and the SSF, it is a simple matter to enter the S-N data and determine the allowable cycles (N). However, in a lap shear joint where the shear flow induced load transfer is independent of the gross area uniaxial stress, the SSF will vary throughout the loading cycle. Also, if the gross area uniaxial stress cycle is tension-compression-tension, the SSF will vary due to the different stress concentration factors for tension and compression. For example, taking the latter case of a tension-compression-tension gross area uniaxial stress cycle with no load transfer, the stress concentration factors (K_{TC}), from Section 3.0 for hole (1), are 3.2 for tension and 1.35 for compression. If α and β are equal to 1.0, $SSF_{max} = 3.2$ and $SSF_{min} = 1.35$.

To account for a variable SSF, a numerical solution is developed based on the observation that within a given S-N data set it is possible to find a single equivalent value of SSF, which, when used with the gross area uniaxial stress cycle and applied to the apparent peak stress cycle, the allowable cycles (N) remain a constant. Introducing the S-N data mean (m) and variable (v) stress notation, the numerical solution may be expressed as:

$$N \text{ for } \left[f_{ax_v}, f_{ax_m}, SSF_E \right] = N \text{ for } \left[\frac{f'_{pk_v}}{SSF_E}, \frac{f'_{pk_m}}{SSF_E}, SSF_E \right]$$

Where SSF_E = Equivalent SSF

As part of this solution it is necessary to rearrange the lap shear SSF equation into the form

$$f'_{pk} = \alpha \beta \left[K_{TG} f_{ax} + K_{TB} \theta f_{br} + K_{TS} \tau \right]$$

$$SSF = f'_{pk} / f_{ax}$$

Where f'_{pk} = apparent peak stress

A simple step-by-step procedure to the solution for N and SSF_E is as follows:

Given the fatigue condition

$$\left. \begin{array}{l} f_{ax_{max}}, q_{max} \\ f_{ax_{min}}, q_{min} \end{array} \right\} n \text{ cycles}$$

- 1) Determine f_{ax_v} and f_{ax_m}
- 2) At the desired analysis location within the joint determine $f'_{pk_{max}}$ and $f'_{pk_{min}}$
- 3) Determine f'_{pk_v} and f'_{pk_m}
- 4) Determine $SSF_1 = \frac{f'_{pk_v}}{f_{ax_v}}$ and $SSF_2 = \frac{f'_{pk_m}}{f_{ax_m}}$
- 5) If SSF_1 is equal to SSF_2 , enter S-N data with f_{ax_v} , f_{ax_m} and SSF_1 to determine allowable cycles (N).
 $SSF_E = SSF_1 = SSF_2$
- 6) If SSF_1 is not equal to SSF_2 , enter S-N data with f_{ax_v} , f_{ax_m} and SSF_1 to determine allowable cycles N_1 . Enter S-N data with f'_{pk_v} / SSF_1 , f'_{pk_m} / SSF_1 and SSF_1 to determine allowable cycles N_2 .
If $N_1 > N_2$ increase SSF_1 until $N_1 = N_2$
If $N_1 < N_2$ decrease SSF_1 until $N_1 = N_2$
Allowable cycles (N) = $N_1 = N_2$
 $SSF_E = SSF_1$ at $N_1 = N_2$

Figure 3.0 presents typical curves of N_1 and N_2 versus SSF_1 and clearly shows that there is only one unique solution for N and SSF_E .

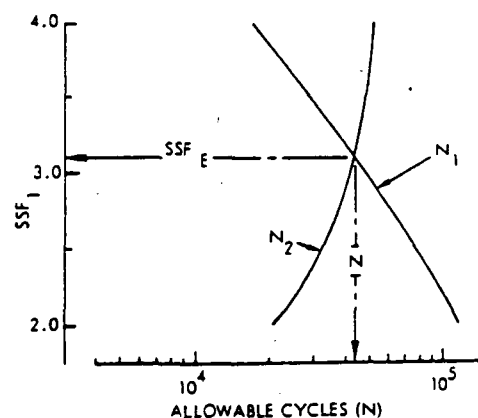


FIGURE 3.0 NUMERICAL SOLUTION FOR N AND SSF_E

Under complex dynamic loading it is possible for the f_{ax} and q cycles to be out of phase. In such a case, the solution should be repeated for different time intervals to find the most critical values for N and SSF_2 .

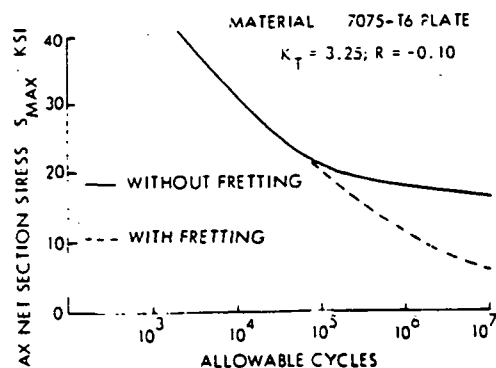


FIGURE 4.0 EFFECTS OF FRETTING ON NOTCHED SPECIMEN FATIGUE ALLOWABLES

S-N Data

S-N data suitable for fatigue analysis of mechanically fastened joints must be based on joint data. Also, to be compatible with the SSF-method of fatigue analysis the S-N data must be expressed in terms of SSF or K_m .

In Figure 4.0 the results of Fatigue Tests on notched specimens, with and without fretting, are presented. (2) The specimens are machined from 7075-T6 plate material and notched to a $K_m = 3.25$. The figure shows the reduction in fatigue allowables in the low stress-high cycle region of the S-N curve, when fretting is present, is considerable. At 10^6 cycles, for example, the fatigue allowables are reduced by 40%.

Since fretting does significantly change the shape of the S-N curve and cannot be avoided in joints, the trends of Figure 4.0 are used to modify the readily available notched S-N data for 7075-T6 plate material. The modified notched S-N data are considered applicable to joints and are called joint S-N data. By taking this approach the re-

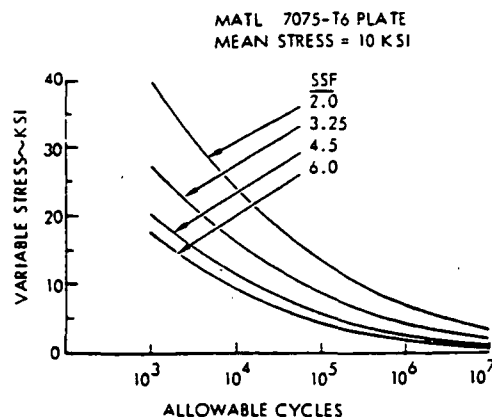


FIGURE 5.0 JOINT S-N DATA BASED ON NOTCHED DATA WHEN FRETTING

sulting joint S-N data are still expressed in terms of SSF or K_m and can be used with the SSF-method of fatigue analysis.

To provide a consistent method to modify the notched S-N data to joint S-N data it is argued that the cycle relationships of Figure 4.0 between the notched curve and the notched curve with fretting, at any given value of allowable cycles on the notched curve, will remain a constant for all values of K_m . Therefore, the two curves of Figure 4.0 can be replotted in the form N_{joint} versus $N_{notched}$. Deriving equations to fit this curve will give:

$$\text{Branch (1) } \log N_{joint} = \log N_{notched}$$

$$\text{Branch (2) } \log N_{joint} = .375 \log N_{notched} + 3.0$$

$$\text{Branch (3) } \log N_{joint} = .198 \log N_{notched} + 4.03$$

These equations are used to compute values of N_{joint} until N_{joint} equals approximately 10^6 cycles. At this point the curves are faired to intercept the abscissa at 10^6 cycles. Examples of the joint S-N data generated in this manner for 7075-T6 plate material are presented in Figure 5.0.

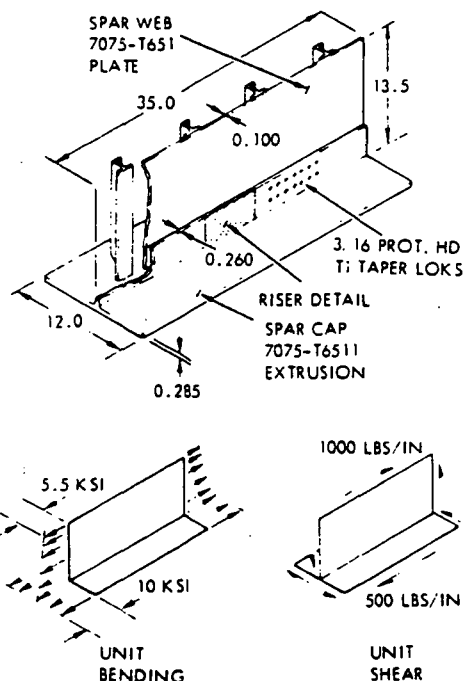


FIGURE 6.0 MODEL A - SINGLE LAP SHEAR JOINT

3.0 Derivation of Stress Concentration Factors

To derive the stress concentration factors, a typical spar web to cap single lap shear joint with two rows of fasteners is analyzed using a computerized linear finite element displacement method of analysis. The structural features of this typical joint are represented in two mathematical

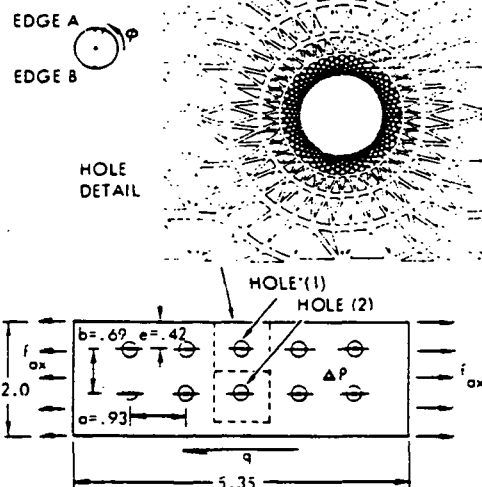
models, Model 'A' and Model 'B'. A brief description of these models and their method of loading is given below.

Finite Element Models

The structure considered in Model 'A' is shown in Figure 6.0; in this model the web, cap and stiffeners are simulated, using a coarse grid network of isotropic triangular membrane plate elements and the fasteners are simulated using linear shear springs. Two sets of external loads are applied, a unit bearing condition with an uniaxial stress of 10 ksi at the cap riser decaying to 5.5 ksi at the edge of the web, and a unit shear condition with a constant shear flow of 1000 lb/in in the web. The intent of Model 'A' is to provide boundary loads (inplane stresses and fastener loads) for the more detailed Model 'B'.

The riser detail, shown hatched in Figure 6.0 and considered in Model 'B', is presented in Figure 7.0. The riser detail is simulated using the same type of element as used in Model 'A', except in Model 'B' the grid size is reduced. The grid size around the two holes of interest, holes (1) and (2), in particular, is reduced to an extremely fine grid for maximum accuracy. In Model 'B' the influence of a varying fastener bearing area with load is also recognized. A special program is used which considers the fastener as a series of rigid radial spokes, each spoke being connected to a grid point around the periphery of the hole. The fastener load is applied at the hub of these radial spokes. Since the actual fastener cannot transmit radial tension loads, the radial spokes must also satisfy this condition. The program is therefore arranged to iterate until all tension spokes are eliminated and only compression spokes remain to react the applied loading. It should be noted that a neat fitting fastener is the reference condition and no fastener interference is considered in this analysis.

3/16 DIA FASTENER - NEAT FIT (TYPICAL)



SIGN CONVENTION - POSITIVE LOADING SHOWN
 NEGATIVE LOADING OPPOSITE

FIGURE 7.0 MODEL B RISER DETAIL

To load Model 'B' the unit boundary loads from Model 'A' are factored and added to form combined cases. Twenty-seven (27) combined load cases are considered and cover a range of uniaxial riser stresses from -20.0 to 30.0 ksi with shear flows from 0 to 3728 lbs/in. To be consistent with the actual wing combined loading, the shear flow is taken negative when the uniaxial riser stress is negative. The sign convention used throughout the analysis is shown in Figure 7.0.

Finite Element Analysis Results

In interpreting the results of the finite element analysis, tangential stresses are used

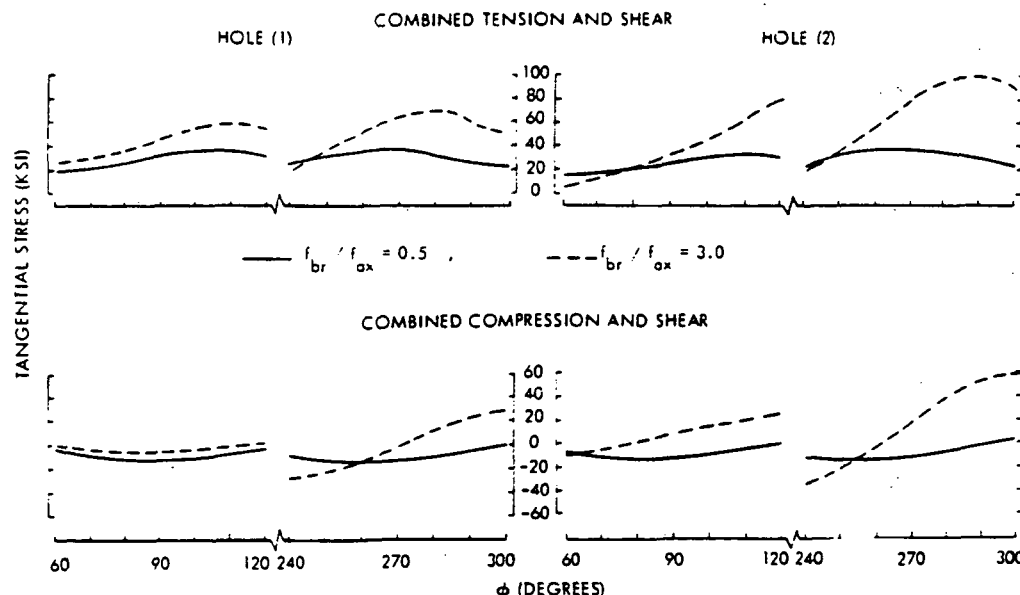


FIGURE 8.0 TANGENTIAL STRESS DISTRIBUTION, LOADED HOLES
 IN UNIAxIAL STRESS FIELD OF 10 KSI

instead of the more common maximum and minimum principal stresses. This approach is taken because, in fatigue analysis, it is a requirement that the stresses acting on common planes be compared and used to compute damage. The use of tangential stresses ensures this requirement is met. Furthermore if it is assumed the tension loading is the most important loading component in fatigue, no significant error is introduced as the tangential stress and maximum principal stress are, in essence, the same in the highly stressed region of the hole.

Comparison of the tangential stress distributions with increasing shear flow clearly show the significance of fastener load transfer. Figure 8.0 illustrates this trend and shows the tangential stress for holes (1) and (2) as a function of angular location ϕ . The values plotted are for a uniaxial tension and compression riser stress of 10 ksi with two values of fastener load transfer, f_{br}/f_{ax} equal to 0.5 and 3.0. It should be noted that, to relate the finite element results to the fatigue analysis method, the uniaxial riser stress is now taken equal to the gross area uniaxial stress, f_{ax} , defined in Section 2.0.

From Figure 8.0 it is immediately apparent the behavior of the tangential stress in compression is considerably different to the more classic behavior of the tangential stress in tension. For example, at hole (1), edge A, the peak values in compression are in the range 0.5 to 1.2 times the uniaxial stress; while the peak values in tension are in the range of 3.6 to 5.9 times the uniaxial stress. Also, the figure shows the angular location of these peak values do not coincide, the angular locations for both tension and compression being a function of the amount of fastener load transfer or shear flow.

A fatigue analysis method, which recognizes the tangential stress distribution as a variable, is extremely cumbersome. Therefore, in the derivation of the stress concentration factors the following simplifying assumptions are made:

- (1) Under combined tension and shear loading it is assumed the peak tangential stress is equal to the calculated peak tangential stress and no correction is applied for location. This is conservative, but not overly so, as the arc formed by the points of the calculated peak tangential stresses, and the stress gradients within this arc, are small for the range of loading investigated. Figure 9.0 shows the variation in the angular location of the calculated peak tangential stress as a function of the f_{br}/f_{ax} ratio. The arc shown is approximately 20° for the f_{br}/f_{ax} range 0 to 4.0.
- (2) Under combined compression and shear loading it is a requirement for fatigue analysis that the tangential stresses act at the same location as the peak tangential stresses for combined tension and shear loading. It is assumed that this requirement can be adequately satisfied by using average values of tangential stress acting within a common arc. In the analysis, the arc formed by the points of the calculated peak tangential stresses under combined tension and shear loading is used.

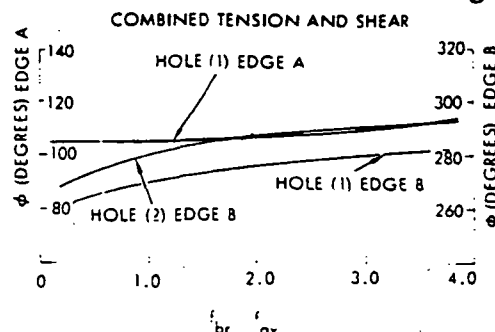


FIGURE 9.0 VARIATION IN ANGULAR LOCATION OF PEAK TANGENTIAL STRESS

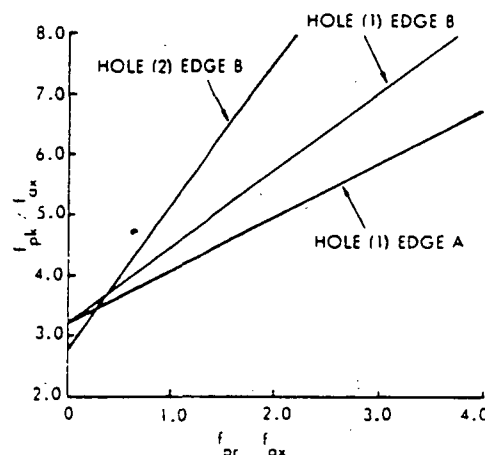


FIGURE 10.0 VARIATION OF PEAK STRESS RATIO COMBINED TENSION AND SHEAR

Applying assumptions (1) and (2) to the finite element results yield the curves presented in Figures 10.0 and 11.0. In both figures the variation of the peak stress ratio, f_{pk}/f_{ax} , is plotted versus the ratio, f_{br}/f_{ax} , where f_{pk} is the peak tangential stress. It should be noted that, in Figure 11.0, f_{pk} is not the true value of the peak tangential stress, but the average value within the considered common arc. Also, as the tangential stress under uniform bearing is always positive (tension), irrespective of the direction of the bearing load, f_{br} is always taken positive.

Combined Tension and Shear Case

Figure 10.0 gives the variation in the peak stress ratio for the combined tension and shear case. The results are linear, but show significant differences in slopes, the slopes increasing when moving from hole (1) edge A to hole (2) Edge B. This difference in slopes is the influence of shear stress on the peak tangential stress and is the reason for the expansion in the stress severity equation discussed in Section 2.0. The curve for Hole (2) Edge A is omitted, as this location is not critical.

The equations which describe these curves, rearranged to give the peak tangential stress, are as follows:

$$\text{Hole (1) Edge A, } f_{pk} = 3.2 f_{ax} + 0.9 f_{br}$$

$$\text{Hole (1) Edge B, } f_{pk} = 3.2 f_{ax} + 1.3 f_{br}$$

$$\text{Hole (2) Edge B, } f_{pk} = 2.5 f_{ax} + 2.4 f_{br}$$

Now, using the arguments that the shear stress component of the peak tangential stress at hole (1) Edge A is small, and the bearing stress component is constant at all locations, it is possible to separate the bearing and shear stress components of the peak tangential stress. Proceeding in this manner, the equations may be rewritten in the form:

$$\text{Hole (1) Edge A, } f_{pk} = 3.2 f_{ax} + 0.9 f_{br}$$

$$\text{Hole (1) Edge B, } f_{pk} = 3.2 f_{ax} + 0.9 f_{br} + 0.4 f_{br}$$

$$\text{Hole (2) Edge B, } f_{pk} = 2.8 f_{ax} + 0.9 f_{br} + 1.5 f_{br}$$

The additional terms being the shear stress component expressed as a function of the bearing stress. From the finite element results the bearing stress can be redefined in terms of shear stress (τ). Making this substitution and taking Edge B as the critical location, the final equations for holes (1) and (2) for the combined tension and shear case become:

$$\text{Hole (1), } f_{pk} = 3.2 f_{ax} + 0.9 f_{br} + 0.84 \tau$$

$$\text{Hole (2), } f_{pk} = 2.8 f_{ax} + 0.9 f_{br} + 2.2 \tau$$

Introducing the stress concentration factor notation of Section 2.0

$$\text{Hole (1), } K_{TG} = 3.2, K_{TB} = 0.9, K_{TS} = 0.84$$

$$\text{Hole (2), } K_{TG} = 2.8, K_{TB} = 0.9, K_{TS} = 2.2$$

Combined Compression and Shear Case

Figure 11.0 gives the variation in the peak stress ratio for the combined compression and shear case. Unlike the curves for combined tension and shear, these curves are non-linear, but exhibit the same differences in slopes due to shear stress.

Also, with increasing f_{br}/f_{ax} values, the curves cross the abscissa showing that the tangential stresses, within the arc of interest, reverse and go into tension if the ratio of f_{br}/f_{ax} is high.

The equations which describe these curves, rearranged to give the peak tangential stress, are as follows. Two sets of equations are required:

$$\text{Range } -6.0 \leq f_{br}/f_{ax} \leq 0.0$$

Hole (1) Edge A,

$$f_{pk} = 1.053 f_{ax} + (-0.055 f_{br}/f_{ax} + .087) f_{br}$$

Hole (1) Edge B,

$$f_{pk} = 1.35 f_{ax} + (-0.095 f_{br}/f_{ax} + .263) f_{br}$$

Hole (2) Edge B,

$$f_{pk} = 1.35 f_{ax} + (-0.227 f_{br}/f_{ax} + .763) f_{br}$$

$$\text{Range } -\infty < f_{br}/f_{ax} < -6.0$$

$$\text{Hole (1) Edge A, } f_{pk} = 4.0 f_{ax} + 0.9 f_{br}$$

$$\text{Hole (1) Edge B, } f_{pk} = 4.0 f_{ax} + 1.3 f_{br}$$

$$\text{Hole (2) Edge B, } f_{pk} = 4.0 f_{ax} + 2.4 f_{br}$$

Applying the same arguments as used for the combined tension and shear case, the final equations for Holes (1) and (2) for combined compression and shear become:

$$\text{Range } -6.0 \leq f_{br}/f_{ax} \leq 0.0$$

Hole (1)

$$f_{pk} = 1.35 f_{ax} + (-0.055 f_{br}/f_{ax} + .087) f_{br} + (-0.084 f_{br}/f_{ax} + .368) \tau$$

Hole (2)

$$f_{pk} = 1.35 f_{ax} + (-0.055 f_{br}/f_{ax} + .087) f_{br} + (-0.221 f_{br}/f_{ax} + .984) \tau$$

$$\text{Range } -\infty < f_{br}/f_{ax} < -6.0$$

$$\text{Hole (1), } f_{pk} = 4.0 f_{ax} + 0.9 f_{br} + 0.84 \tau$$

$$\text{Hole (2), } f_{pk} = 4.0 f_{ax} + 0.9 f_{br} + 2.2 \tau$$

Again, introducing the stress concentration factor notation of Section 2.0

$$\text{Range } -6.0 \leq f_{br}/f_{ax} \leq 0.0 \quad -\infty < f_{br}/f_{ax} < -6.0$$

Hole (1)

K_{TG}	1.35	4.0
K_{TB}	$(-0.055 f_{br}/f_{ax} + .087)$	0.9
K_{TS}	$(-0.084 f_{br}/f_{ax} + .368)$	0.84

Hole (2)

K_{TG}	1.35	4.0
K_{TB}	$(-0.055 f_{br}/f_{ax} + .087)$	0.9
K_{TS}	$(-0.221 f_{br}/f_{ax} + .984)$	2.2

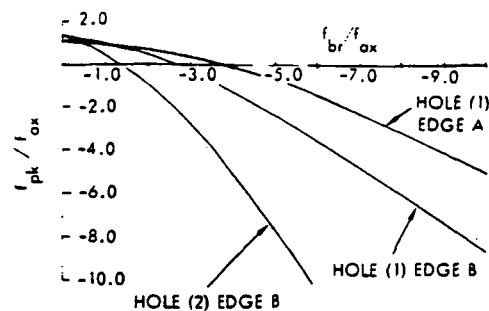


FIGURE 11.0 VARIATION OF PEAK STRESS RATIO COMBINED COMPRESSION AND SHEAR

Application

To apply the stress concentration factors to a single lap shear joint requires an understanding of the joint geometry and internal load distribution. If for instance, holes (1) and (2) shown in Figure 7.0 are considered to be in rows (1) and (2), respectively, the riser detail is considered as element (1) and the attaching web is considered as element (2). The stress concentration factors presented can be subscripted as follows:

Element (1), Row (1); K_{TG11} , K_{TB11} , K_{TS11}

Element (1), Row (2); K_{TG12} , K_{TB12} , K_{TS12}

Element (2), Row (1); K_{TG21} , K_{TB21} , K_{TS21}

Element (2), Row (2); K_{TG22} , K_{TB22} , K_{TS22}

Now, to maintain the same geometry and shear stress distribution as element (1), the hole location in element (2) must be interchanged. Hence:

$$K_{TG22} = K_{TG11}, K_{TB22} = K_{TB11}, K_{TS22} = K_{TS11}$$

$$\text{and } K_{TG21} = K_{TG12}, K_{TB21} = K_{TB12}, K_{TS21} = K_{TS12}$$

For a lap shear joint with one row of fasteners the stress concentration factors with subscripts (11) are used for elements (1) and (2). However, to account for the higher shear stresses a factor of 2.0 is applied to K_{TS} .

Limitations

The finite element results presented are based on the following geometrical ratios.

$$e/D = 2.2, a/D = 4.9, b/D = 3.6$$

Where e is the edge distance, a is the pitch, b is the distance between rows and D the fastener diameter. However, further analysis with the fasteners increased to 1/4 inches in diameter, show no significant change in the results. The lower limit for the geometrical ratios investigated can therefore be taken as:

$$e/D = 1.68, a/D = 3.7, b/D = 2.76$$

Using the above ratios it is considered the stress concentration factors presented can be safely applied to single lap shear joints which fall within the range

$$1.5 \leq e/D \leq 2.5$$

$$3.5 \leq a/D \leq 5.0$$

$$2.75 \leq b/D \leq 4.0$$

4.0 Analytical Fastener Tilt Factor (θ)

As previously stated in Section 2.0, the action of the load transfer causes the fastener system to deform (tilt) and peaking of the bearing stress occurs at the faying surface of the joint. This peaking of the bearing stress is a function of the joint configuration and will vary depending on the material of the plate and fastener, joint thickness to fastener diameter ratio and type of fastener head.

To derive a linear solution for the peak bearing stress at the faying surface and, therefore, the tilt factor (θ) to be applied to the uniform bearing stress, requires an extremely sophisticated method of analysis. In addition to the usual plate stiffness, fastener bending and shear stiffness terms, the method should include terms to account for the tension load introduced into the fastener system by the clamping action of the fastener head. Harris, Ojalvo and Hooson⁽³⁾ proposed a linear solution for the peak bearing stress, in a single lap shear joint, considering the fastener as a short beam on an elastic foundation. The solution, however, did not include fastener tension effects and imposed the arbitrary boundary conditions of a negligible-head or rigid-head. To expand their solution to include the tension load effects would be a formidable task and is not attempted. Instead, to derive the equations for the tilt factor,

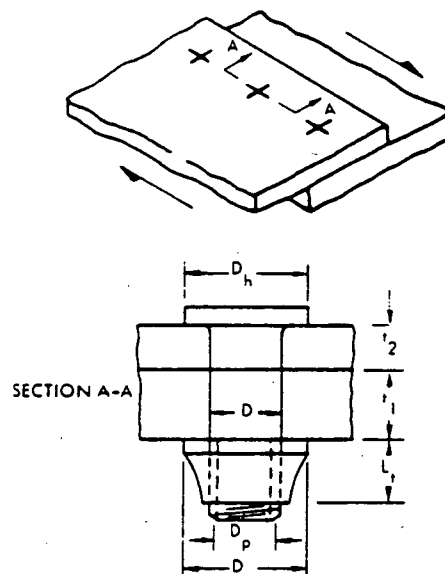


FIGURE 12.0 JOINT GEOMETRY

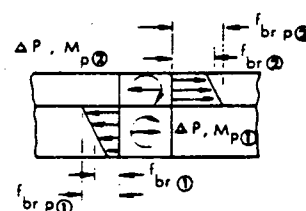
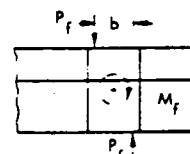


PLATE BEARING FORCES



FASTENER TENSION FORCES

$$M = \Delta P/2 (t_1 + t_2) = M_{p1} + M_{p2} + M_f$$

FIGURE 13.0 JOINT INTERNAL FORCE SYSTEMS

reliance is placed on test observations to formulate the approximate linear theory presented.

The failure mode of typical fastener critical single shear tests of high strength titanium fasteners in an aluminum joint is nearly always tension, the failure occurring at the root area of the fastener or by stripping the nut. Also, post inspection of the failed fastener usually reveals no evidence to suggest excessive bending or shear deformation. This behavior indicates the tension load is high and is of sufficient magnitude to keep the fastener essentially straight. Because of this, the tension term is assumed to be the predominate term in the fastener stiffness equation. The bending and shear terms, being small, are neglected and the fastener assumed rigid for these modes of deformation.

Figures 12 and 13 define the geometry and internal force systems considered in the derivation of the tilt factors. The assumption that the fastener is rigid for bending and shear permits a linearly varying bearing stress distribution to be used.

The resulting equations for the tilt factors are as follows: In the interest of brevity, only the final equations used to calculate the tilt factors are presented. By definition

$$\theta = \frac{\text{Peak Hole Bearing Stress}}{\text{Uniform Hole Bearing Stress}} = f_{br} / f_{br}$$

for element (1), thickness (t_1)

$$\theta_1 = 1 + 3 S_r t_1^2 (t_1 + t_2) / (t_1^3 + t_2^3)$$

and for element (2), thickness (t_2)

$$\theta_2 = 1 + 3 S_r t_2^2 (t_1 + t_2) / (t_1^3 + t_2^3)$$

In the above equations S_r is the relative stiffness of the plate (k_p) to the total stiffness of the plate and fastener ($k_p + k_f$)

$$S_r = k_p / k_p + k_f : k_p = \frac{3E}{12} (t_1^3 + t_2^3)$$

$$\text{and } k_f = \frac{Cb^2 A_e E_f}{(t_1 + t_2)}$$

The term C is a pre-load factor to account for fastener pretension load caused by nut installation torque and b is the fastener effective moment arm defined by the equation

$$b = \frac{4}{3\pi} \frac{(D_s^3 - D^3)}{(D_s^2 - D^2)}$$

The term A_e is the equivalent fastener shank area over length ($t_1 + t_2$) and accounts for fastener thread and nut effects

$$A_e = \frac{4}{\pi} \left\{ \frac{(t_1 + t_2)}{D^2} + .55 L_t \left[\frac{1}{D_p^2} + \frac{1}{(D_n^2 - D^2)} \frac{E_f}{E_n} \right] \right\}$$

Where

D = Fastener Shank Diameter (ins)

D_h = Fastener Head Diameter (ins)

D_p = Thread Pitch Diameter (ins)

D_n = Nut Outside Diameter (ins)

D_s = D_h or D_n , whichever is the smaller (ins)

L_t = Engaged Thread Length (ins)

E_p, E_f, E_n = Modulus of elasticity for Plate, Fastener and Nut, respectively (psi)

Figure 14.0 shows the result of applying the tilt factor equations to a single lap shear aluminum joint with titanium Taperlok fasteners (shear type) and aluminum torque-off collars. The tilt factors θ_1 and θ_2 versus t_1/D are presented for $t_2/t_1 = .5$ and 1.0.

Countersunk Fastener

To account for the influence of a countersunk fastener it is assumed that the depth of the countersunk head is 5.5 effective.

The thickness of the countersunk plate is, therefore, reduced to:

$$t' = t - D_{csk}/2$$

The reduced thickness (t') is then used in place of the actual thickness (t), to enter Figure 14.0 for θ and to calculate the uniform hole bearing stress (f_{br}).

5.0 Test Correlation

To correlate the fatigue analysis method presented and test, the results from two full scale fatigue test articles, X993 and X995, are used. The structure considered is the inner wing box lower surface assembly between the wing root rib and the inboard engine pylon.

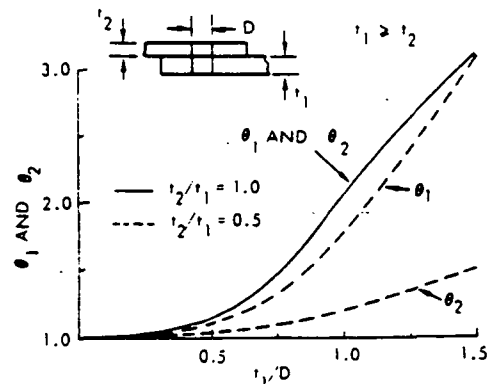


FIGURE 14.0 TILT FACTOR SINGLE LAP SHEAR ALUMINUM JOINT WITH PROTRUDING HEAD TITANIUM TAPER-LOK FASTENERS

The spectrum of loads applied to the X993 and X996 test articles were based on the block method of fatigue testing. The X993 test was an expedited wing fatigue test and designed to yield early data on potential wing fatigue problem areas. The block spectrum of loads was, therefore, reduced to a minimum and had 4 load conditions with a total of 161,000 cycles per lifetime of 30,000 cyclic test hours. The X996 test was the primary wing/fuselage fatigue test and had 18 load conditions with a total of 400,000 cycles per lifetime of 30,000 cyclic test hours. In both the X993 and X996 test spectra the loads were applied in passes of 3000 cyclic test hours, and the load sequence was low-high-low. Also, using the K_T method of fatigue analysis, with notched S-N data, the X993 and X996 test spectra were derived to give the same analytical damage for a $K_T = 4.0$.

Figure 15.0 shows a planform view looking down on the inner wing box lower surface panel assembly and indicates the specific analysis points used in the correlation. The assembly shown consists of: 3 spar caps, 9 surface panels and the attachment of 3 spar webs. The assembly contains 13 spanwise single lap shear joints. The spar caps and surface panels are machined from 7075-T6511 extrusion, and the spar webs are 7075-T651 plate. The spar cap-to-panel and panel-to-panel joints are formed using 60° countersunk head titanium TaperLok fasteners with aluminum collars. The spar web-to-spar cap joints are formed using protruding head titanium TaperLok fasteners with aluminum collars. During assembly the faying surfaces of all joints are coated with sealant and all fasteners are wet installed.

Table 1.0 lists, for the 5 analysis points shown on Figure 15.0, the joint geometry and the empirically derived factors K_N , K_T , and $\alpha\beta$. The empirical factors are based on the test demonstrated fatigue life at each point and are calculated for X993 and X996 using the following methods:

A), K_N - Conventional K_N -method of fatigue analysis using 7075-T6 notched S-N data and considering uniaxial stress only.

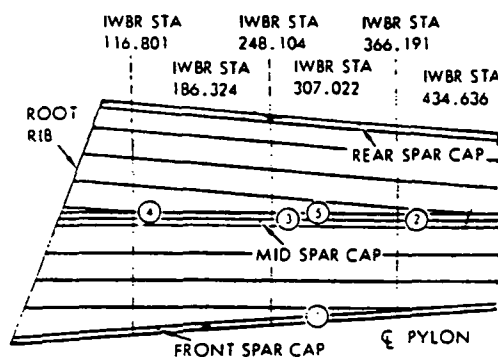


FIGURE 15.0 PLANFORM VIEW OF INNER WING BOX LOWER SURFACE PANEL ASSEMBLY - CORRELATION ANALYSIS POINTS

B), K_T - Conventional K_T -method of fatigue analysis using the 7075-T6 joint S-N data presented in Section 2.0 and considering uniaxial stress only.

C), $\alpha\beta$ - SSF-method of fatigue analysis presented in Section 2.0, considering uniaxial stress and shear flow or load transfer.

The empirical factors K_N and K_T are the same as the 'quality level index' $K'(4)^J$ with the subscripts N and J added to denote the type of S-N data used in their derivation. The empirical factor $\alpha\beta$ is the combined α and β factors discussed in Section 2.0. On the full scale fatigue test articles it was impossible to separate the effects of hole preparation and hole filling; therefore, the α and β factors are combined and referred to as $\alpha\beta$.

Comparing the empirical factors for X993 and X996 shows that the required correlation factors (X996/X993) are a maximum for method A and a minimum for method C, the required correlation factors for method B falling between these extreme values. For example, at point (4) the correlation

TABLE 1.0 JOINT GEOMETRY AND EMPIRICAL FACTORS

POINTS	JOINT GEOMETRY							EMPIRICAL FACTORS					
	FASTENER DATA				PANEL DATA			METHOD A (K_N)		METHOD B (K_T)		METHOD C ($\alpha\beta$)	
	D	HEAD	a	n	t ₁	t ₂	t ₃	X993	X996	X993	X996	X993	X996
①	.25	CSK	1.01	1	.20	.20	.1505	5.10	5.85	4.20	4.55	0.98	0.97
②	.1875	PROT.	0.93	2	.26	.100		4.52	4.90	3.98	4.16	0.88	0.95
③	.1875	PROT.	0.93	2	.26	.100		4.40	4.80	3.80	4.10	0.93	0.99
④	.25	CSK	1.09	1	.25	.212	.1625	5.15	6.17	4.35	4.95	0.96	1.03
⑤	.25	CSK	1.22	1	.25	.25	.2005	4.38	4.90	3.80	4.17	0.91	.87
								4.71	5.32	4.03	4.39	0.93	0.96
								AVG	5.02		4.21		0.945

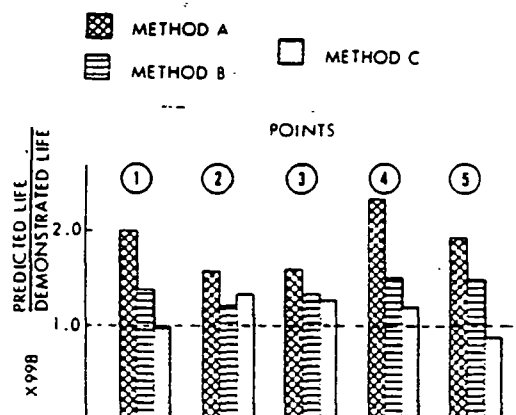


FIGURE 16.0 RATIO OF X998 PREDICTED LIFE, BASED ON X993 EMPIRICAL FACTOR, TO DEMONSTRATED LIFE

factors are 1.23, 1.14 and 1.07 for methods A, B and C, respectively. If the average values are used this trend is maintained, the correlation factors being 1.13, 1.09 and 1.03.

To further compare the empirical factors the scatter about the overall average values shows that the scatter using method A is +23% to -13% of the overall average values of 5.02, the scatter using method B is +18% to -10% of the overall average value of 4.21 and the scatter using method C is +9% to -8% of the overall average value of 7.945.

A comparison of the empirical factors does not necessarily indicate the true accuracy of a method of fatigue analysis, as a small change in the empirical factor can produce a large change in predicted life. Figure 16.0 illustrates this point and shows the ratio of the X998 predicted life, based on the X993 empirical factors, to demonstrated life. The trend is the same as the trend observed for the empirical factors, the life predictions being in the range 1.6 to 2.3, 1.2 to 1.5 and 0.9 to 1.3 times the demonstrated life for methods A, B and C, respectively. The best life prediction for method B of 1.2 and the worst life prediction for method C of 1.3 occur at point (2); at all other points method C gives the best life prediction.

6.0 Conclusions

The correlation of analysis and test results presented in Section 5.0 shows that the best correlation is achieved using method C. As method C is the SSF-method of fatigue analysis and includes fastener load transfer effects, the factor used to define the fatigue quality of a joint is not only a function of the joint geometry, but also of the joint loading. This conclusion then points to the need and importance of such an analysis which considers, say on a wing box, not only the stress due to wing bending, but also the effects on fatigue life of wing shear and torsion. This method then should be considered a valuable tool in developing fatigue test spectra and when comparing fatigue design spectra on structure with different usages. On the C-5A wing, the SSF-method

of fatigue analysis, for single lap shear joints, is being used to determine the effects on the wing structure of different methods of lift distribution control systems and/or fuel utilization sequencing.

Acknowledgments

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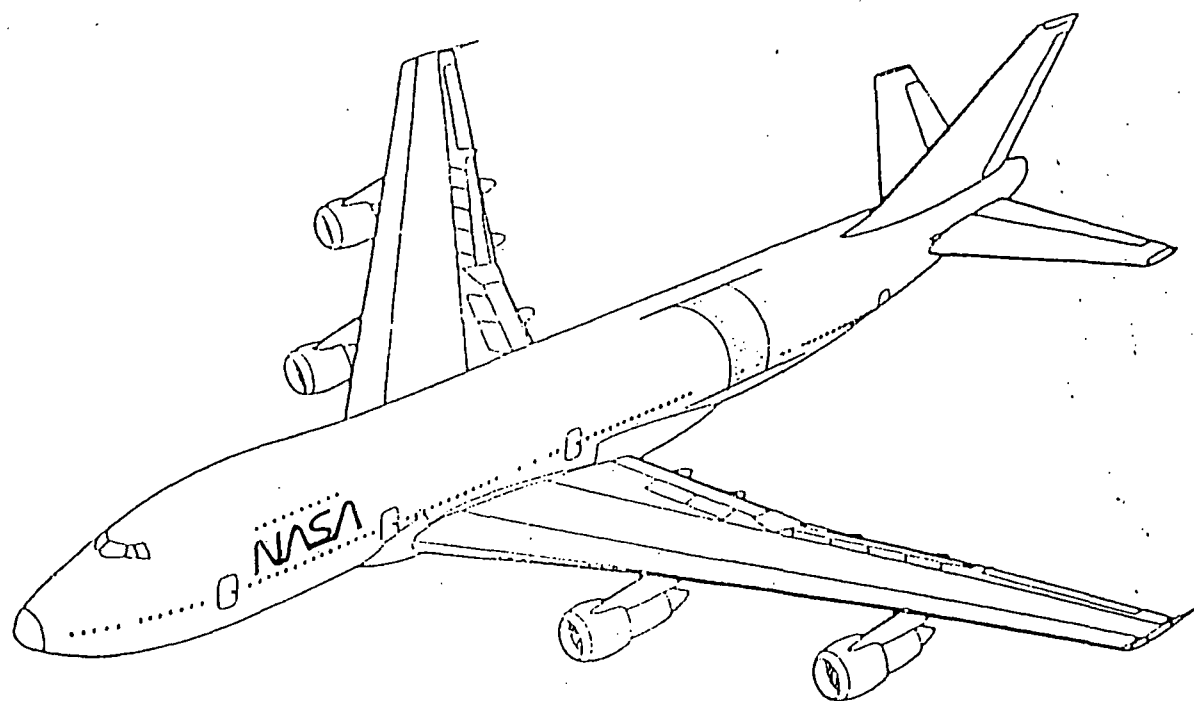
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2. Carroll, J. R., Fatigue of Notched Specimens with Pretting, SMN 376, Internal Report, Lockheed-Georgia Company, Marietta, Georgia, Jan. 1973.
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**SOFIA PHASE II
FINAL REVIEW**



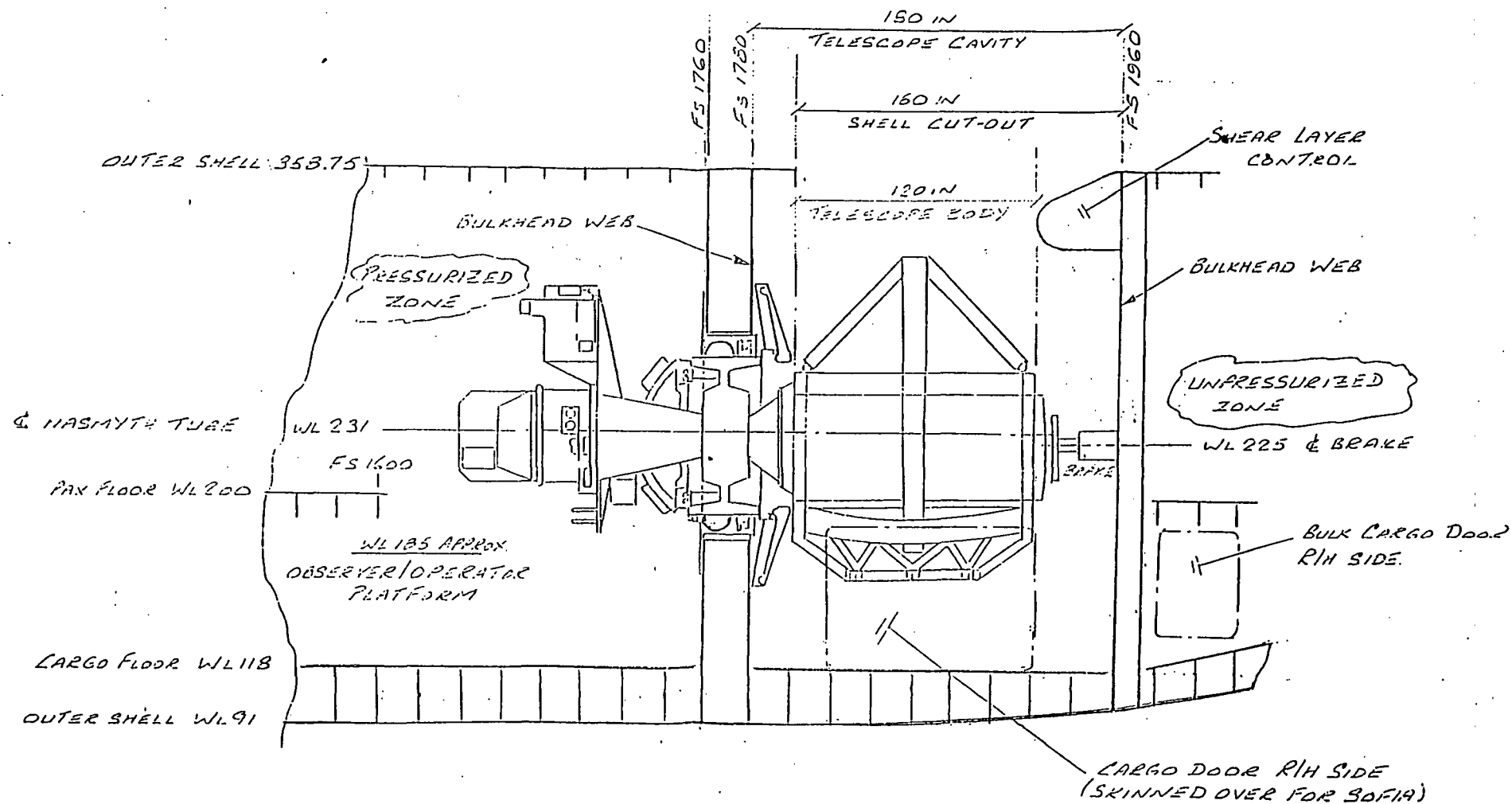
MARCH 8, 1994



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SOFIA ARRANGEMENT





SOFIA



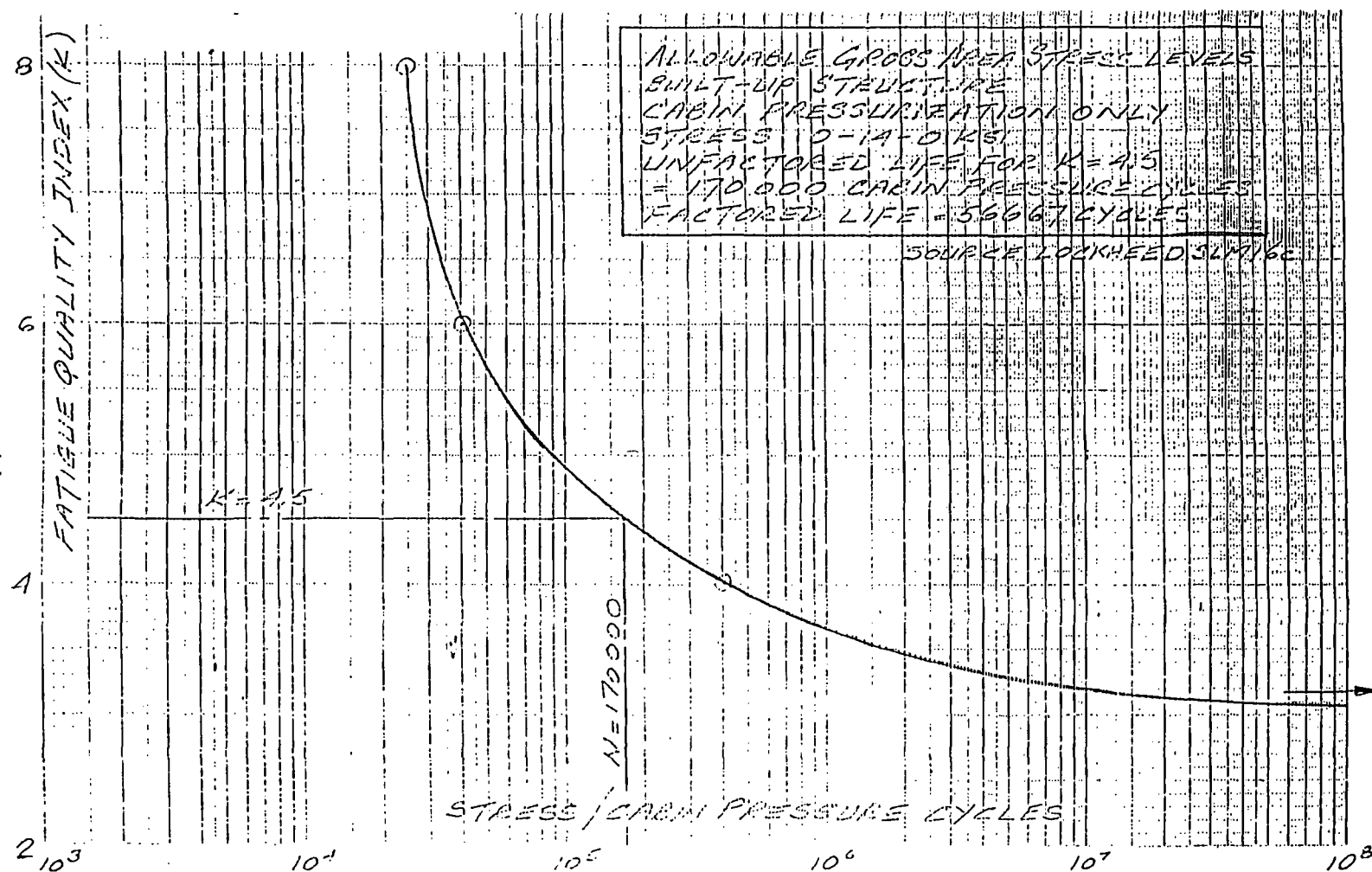
CRITERIA AND ASSUMPTIONS

- **ALLOWABLE STRESS LEVELS FATIGUE CRITICAL ALUMINUM PARTS**
 - FLIGHT & PRESSURIZATION LOADS – 45KSI ULT
 - FLIGHT & PRESSURIZATION LOADS UNINSPECTABLE AREAS – 30KSI ULT
 - PRESSURIZATION LOADS ONLY – 21KSI ULT
- **ABOVE GROSS AREA STRESSES BASED ON**
 - SECTION EFFICIENCY 75%
 - FATIGUE QUALITY INDEX 4.5
- **FOR OUTSTANDING FLANGES WITH NO HOLES**
 - PRESSURIZATION LOAD ONLY – 45KSI ULT



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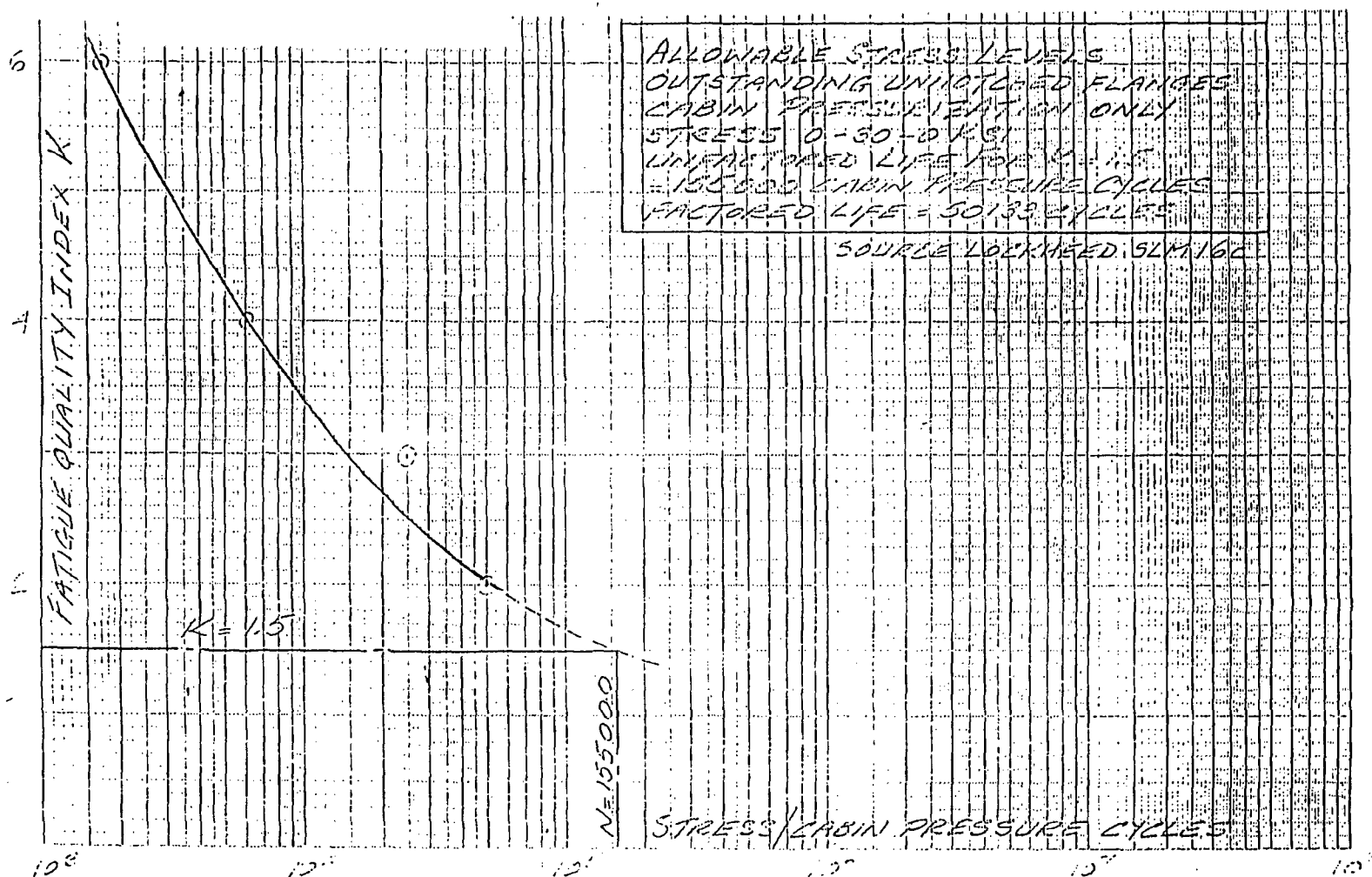
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CRITERIA AND ASSUMPTIONS

- **ALLOWABLE STRESS LEVELS**

- NET SECTION ALLOW YIELD AT LIMIT LOAD
- NET SECTION ALLOW ULTIMATE AT ULTIMATE LOAD

- **STIFFNESS**

- MAINTAIN SAME STIFFNESS AS BASIC 747 AS FAR AS FEASIBLE

- **TELESCOPE MASS PROPERTIES**

- USE LMSC VALUES FROM LMSC/PO16023



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BASELINE FEA MODEL

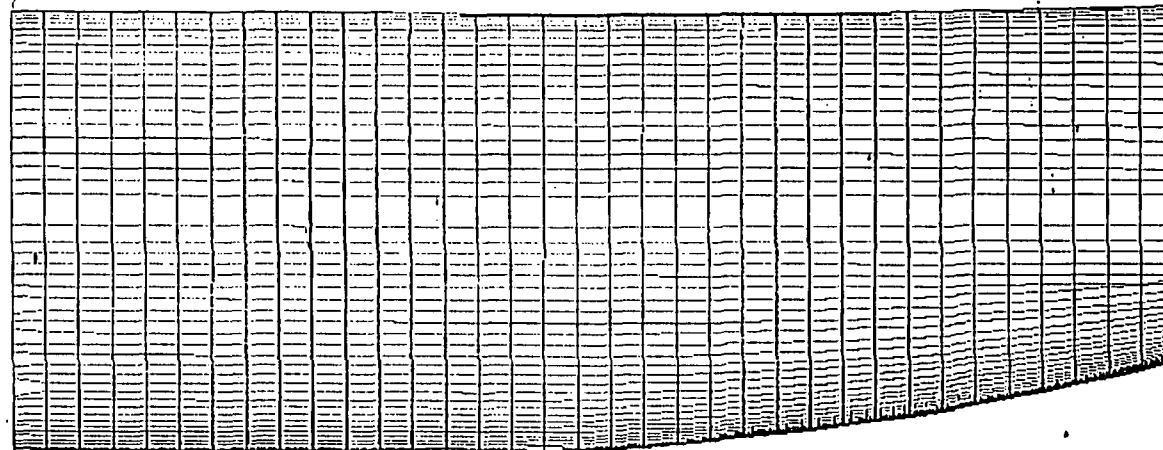
- **DISCRETELY MODELED FS1480-FS2180**
 - 5000 NODES
 - 31000 DOF
- **SUBSTRUCTURE FWD OF FS1480**
 - REACTIONS AT STUB WING TIPS AND FORWARD END OF FUSELAGE (FS900)



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Side View of Aft Fuselage Shell
FS 1480 to FS 2180

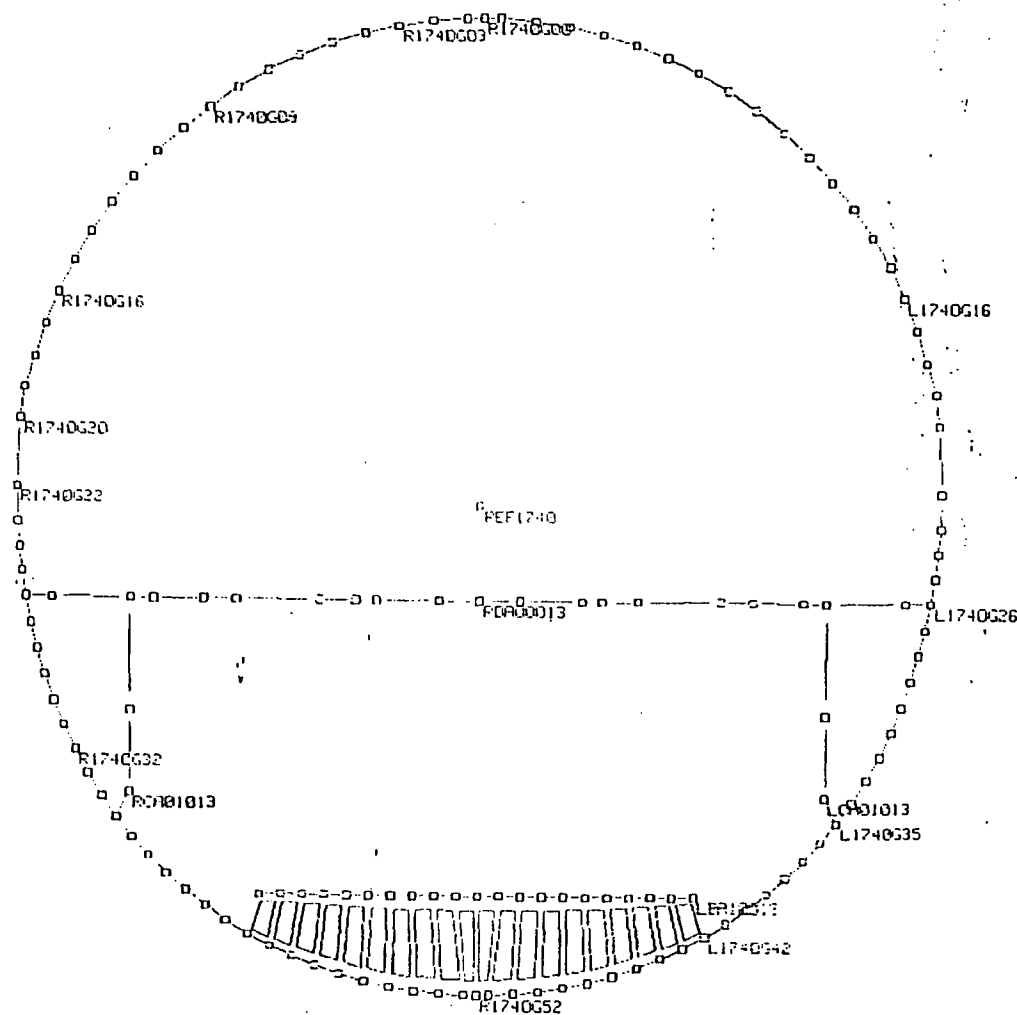




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FS 1740 Cross Section

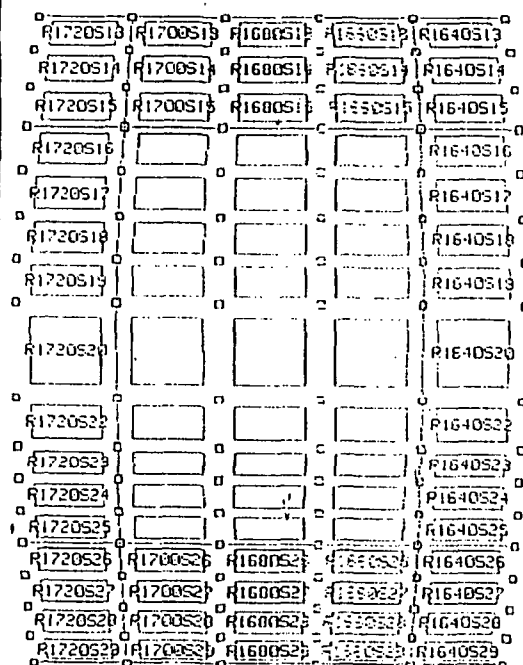




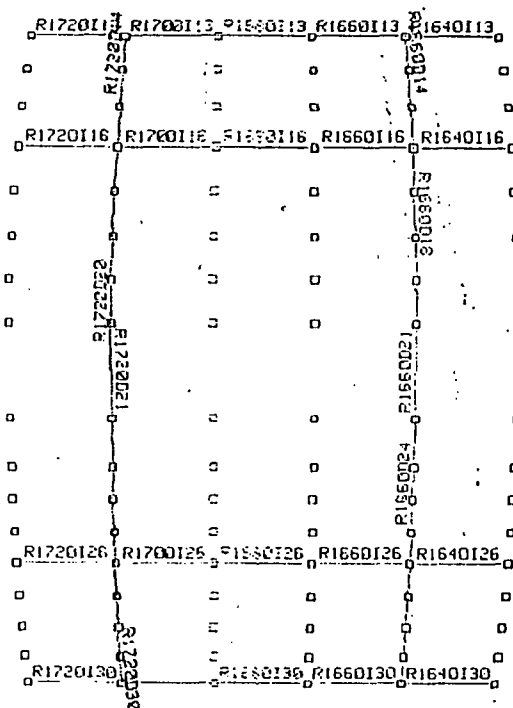
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FS 1640-1740 / Skinned-over Entry Door Area
Panel Elements



Reinforcing Beam Elements



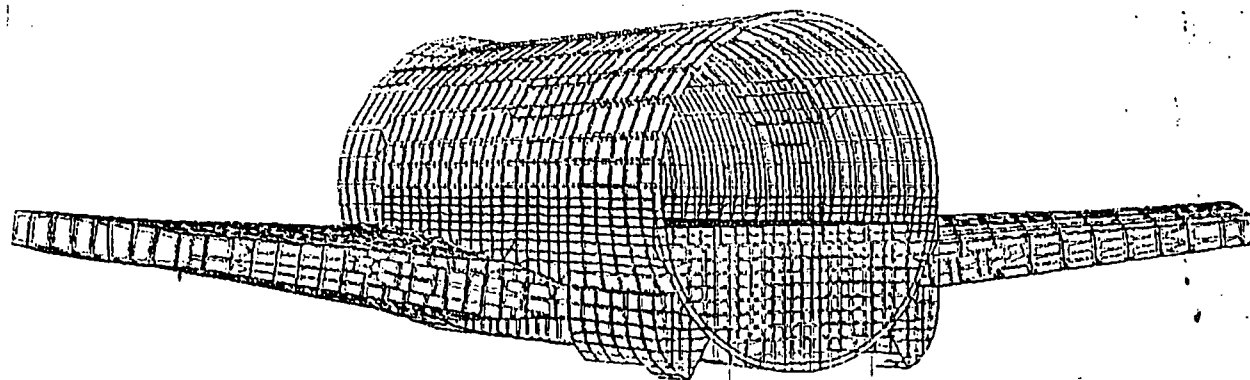




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Boeing 747 Center Section Substructure
FS 900 -- FS 1480 Including Stub Wings





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SOFIA FEA MODEL

- **BASELINE 747 MODEL PLUS**

- FORWARD BULKHEAD ALL ELEMENTS DISCRETELY MODELED
- AFT BULKHEAD BEAM ELEMENTS AND SHEAR WEBS
- TRANSITION DISCRETELY MODELED DOWN TO FASTENER LEVEL AT ONE LOCATION - OTHER LOCATIONS MODELED AS BEAMS
- SURROUND STRUCTURE BEAMS, RODS & SHELL ELEMENTS
- FLOORING BEAMS, RODS AND SHEAR ELEMENTS

FILES UTF HELP QUIT
MACRO RESET SCOPY REDRAW
WINDOW
VIEW LIMITS FONT
ITEM INFO FIND
CENTER CENT C CENT I CENT Z
MOVE I ZOOM R
DISP INT LD

Command Input

Command

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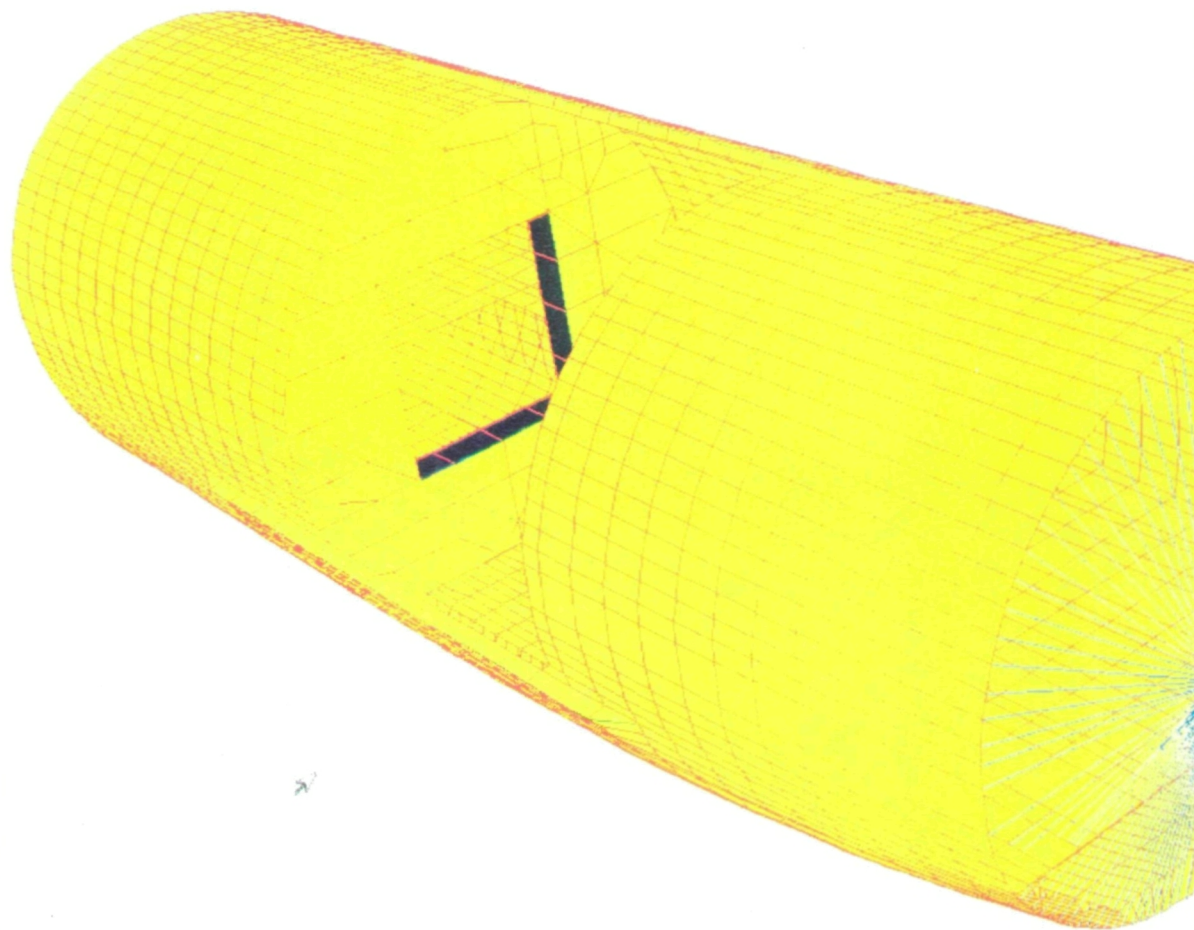
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ELEMENT TYPES

— BCRN
— ROD
— RIGID
— SHPRN
— SHELL

FILE: rbars2180a.s

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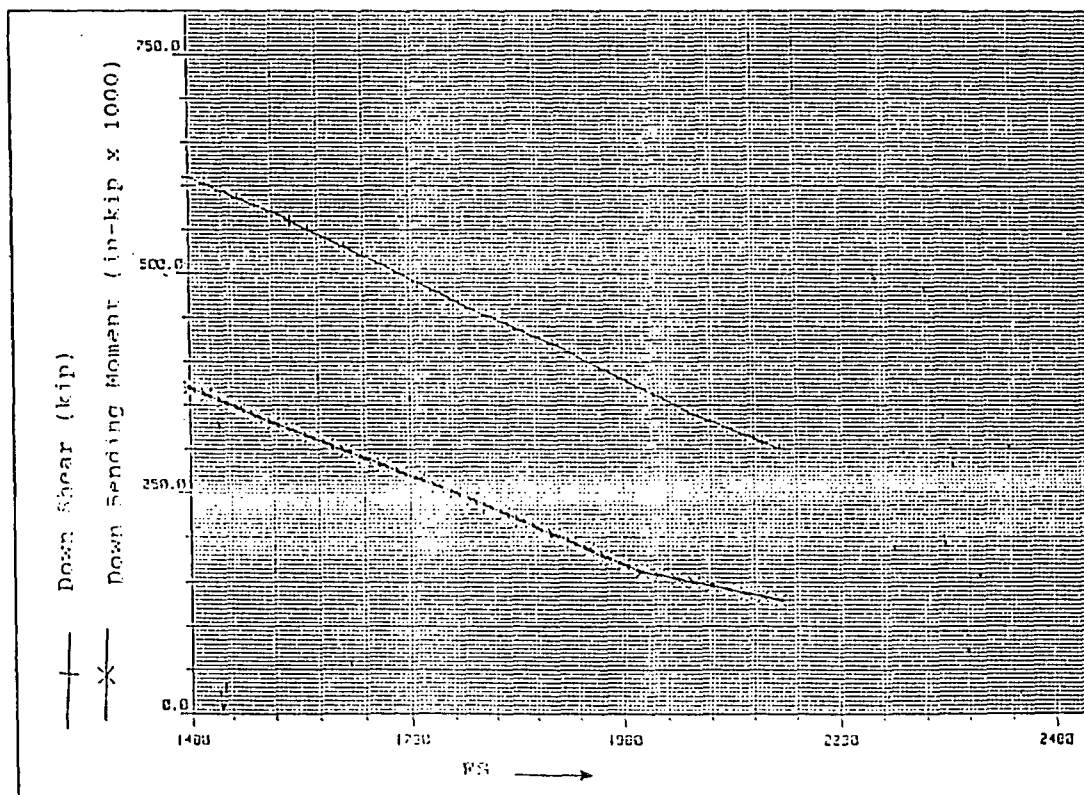
LOADS

- **DEVELOPED FROM ENVELOPE LOADS IN BOEING REPORTS**
- **LOAD CASES**
 - VERTICAL BENDING ENVELOPE
 - LATERAL BENDING ENVELOPE
 - PRESSURE ONLY
 - LATERAL LOAD – LEVEL FLIGHT
 - 2P CONDITION
 - BENDING CASES PLUS ULTIMATE PRESSURE



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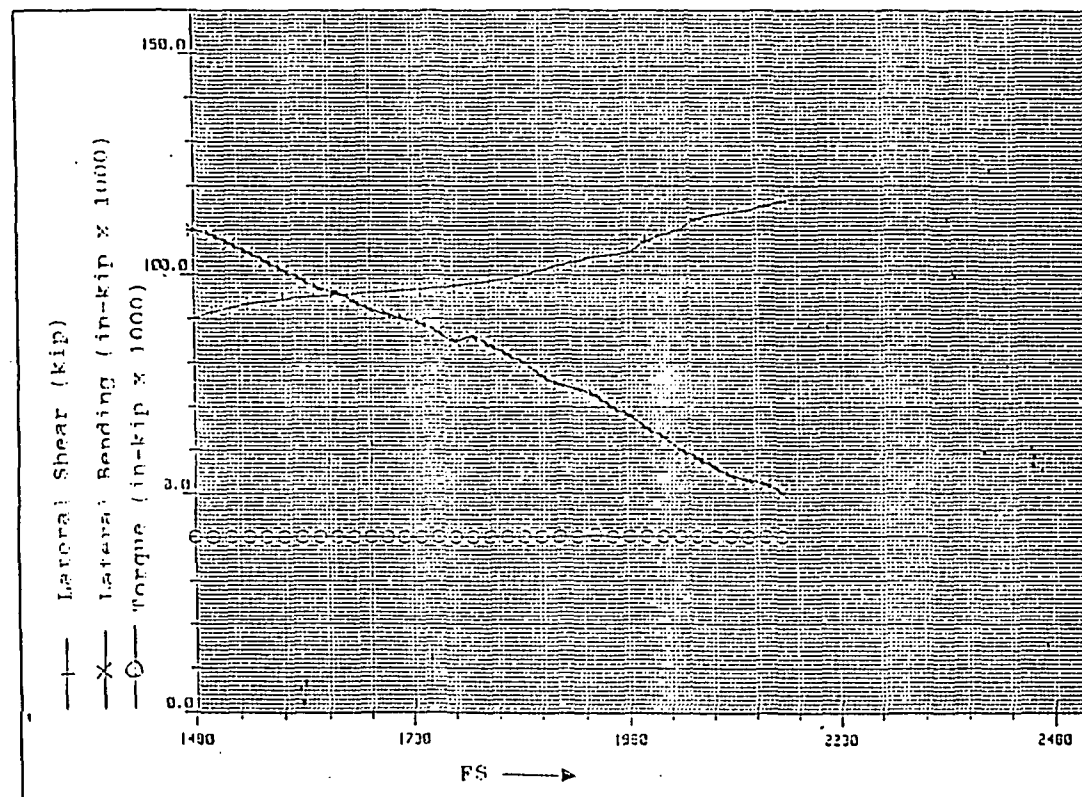
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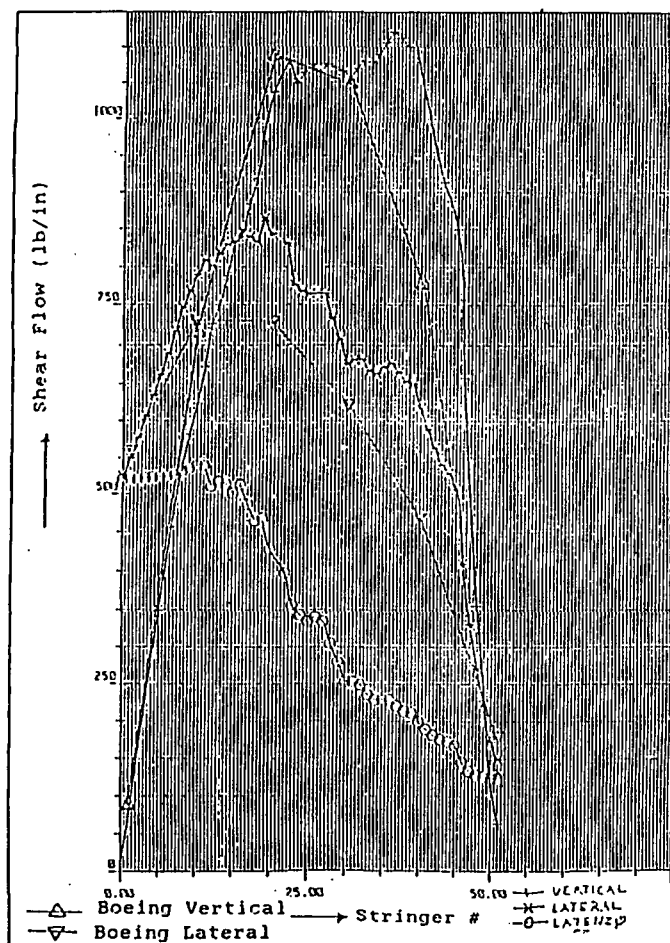


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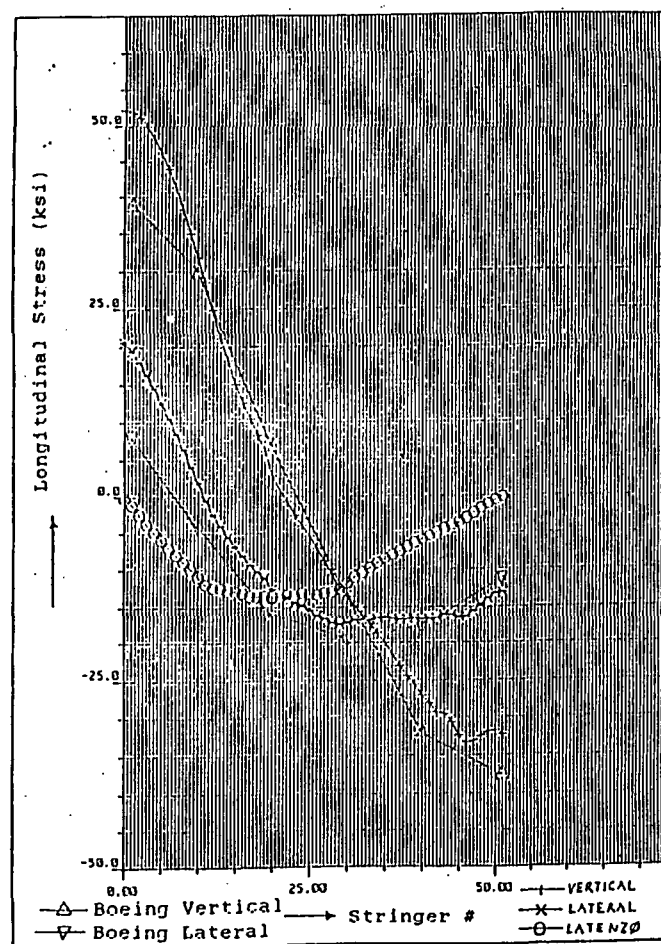
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LOADS/MODEL VALIDATION

Aft fuselage without Doors FS 1740



Aft Fuselage without Doors FS 1740





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747-100 Weight Conditions

Cond.	GW kips	c.g. MAC	IYY in-lb-sec ²	Izz in-lb-sec ²
000	327	34.9%	.258E+09	.374E+09
001	360	13.0%	.305E+09	.422E+09
002	585	13.0	.480E+09	.611E+09

747-100 LIMIT Acceleration Design Conditions

(NY, $\ddot{u}$ apply to Lateral Gust, Nz, $\ddot{u}$ to others,

Gust Conditions at Vc; 375 KEAS at 20kFT, or MO.92 at 40 kFT)

Cond.	Type	GW kips	c.g. %MAC	Alt. KFT	Ny/Nz LIMIT	$\ddot{u}/\ddot{v}$ rad/sec ²
GL01.1	Lat. Gust	360	0.13	20	0.51	0.212
GL02.1	Lat. Gust	360	0.13	40	0.24	0.100
GN01.1	-Gust	360	0.13	20	-1.02	0.363
GN02.1	-Gust	360	0.13	40	-0.16	0.201
GP01.1	+Gust	360	0.13	20	3.02	-0.363
GP02.1	+Gust	360	0.13	40	2.16	-0.201
LL01.2	2WLL	585	0.13	S.L.	2.15	-0.190

2 WLL Two-wheel Level Landing at Maximum Vertical Reaction

MAC	327.8 in
LEMAC	1258 in
S	5500 ft-sq
B	2348 in
LFUS	2702 in
Xtail	2495 in
Ltail	1254.05 in
Sht	1470.7 ft-sq
A	6.96
Aht	3.6
g	32.2 ft/sec-sq

Alt.	20	40kFT
Ve	375	262 KEAS
N	0.836	0.92
CLaf to	0.0736	0.0855 1/deg
Cmaf to	0.0150	0.0084 1/deg
deda	0.3857	0.4481
CLaf	0.0852	0.0959 1/deg
Cmaf	0.0293	-0.0314 1/deg
CYbeta	-1.0258	-1.0258 1/rad
Cnbeta	0.1964	0.1964 1/rad



SOFIA

NASA

FORWARD BULKHEAD

- **DISCRETELY MODELED**

- BULKHEAD WEB
- BEAM WEBS
- BEAM CAPS
- BULKHEAD CAP



SOFIA

NASA

FORWARD BULKHEAD

- **DEFLECTION 0.5" LIMIT AT TELESCOPE MOUNTS**
- **BEAMS 20 INCH DEEP**
- **BEAM WEBS NON-BUCKLING AT LIMIT LOAD**
- **EXTRUDED PRESSURE PANEL**
- **BEAM CAPS 5.6 IN²**
- **BEAM WEBS 0.063 AND 0.080**

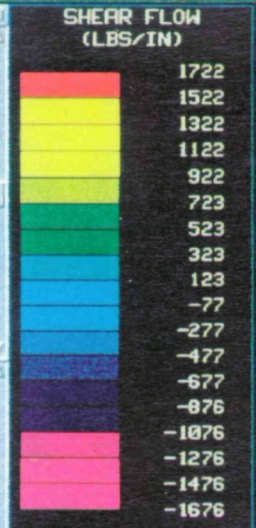


FILES EDIT HELP UNIT
 WINDOW RESET SCRIPT REDRAW
 VIEW LIMITS FONT
 XVIEW UNDO FLOW
 CENTER CENTER CENTER CENTER
 WINDOW WINDOW
 WINDOW CENTER

Command Input
 View 1
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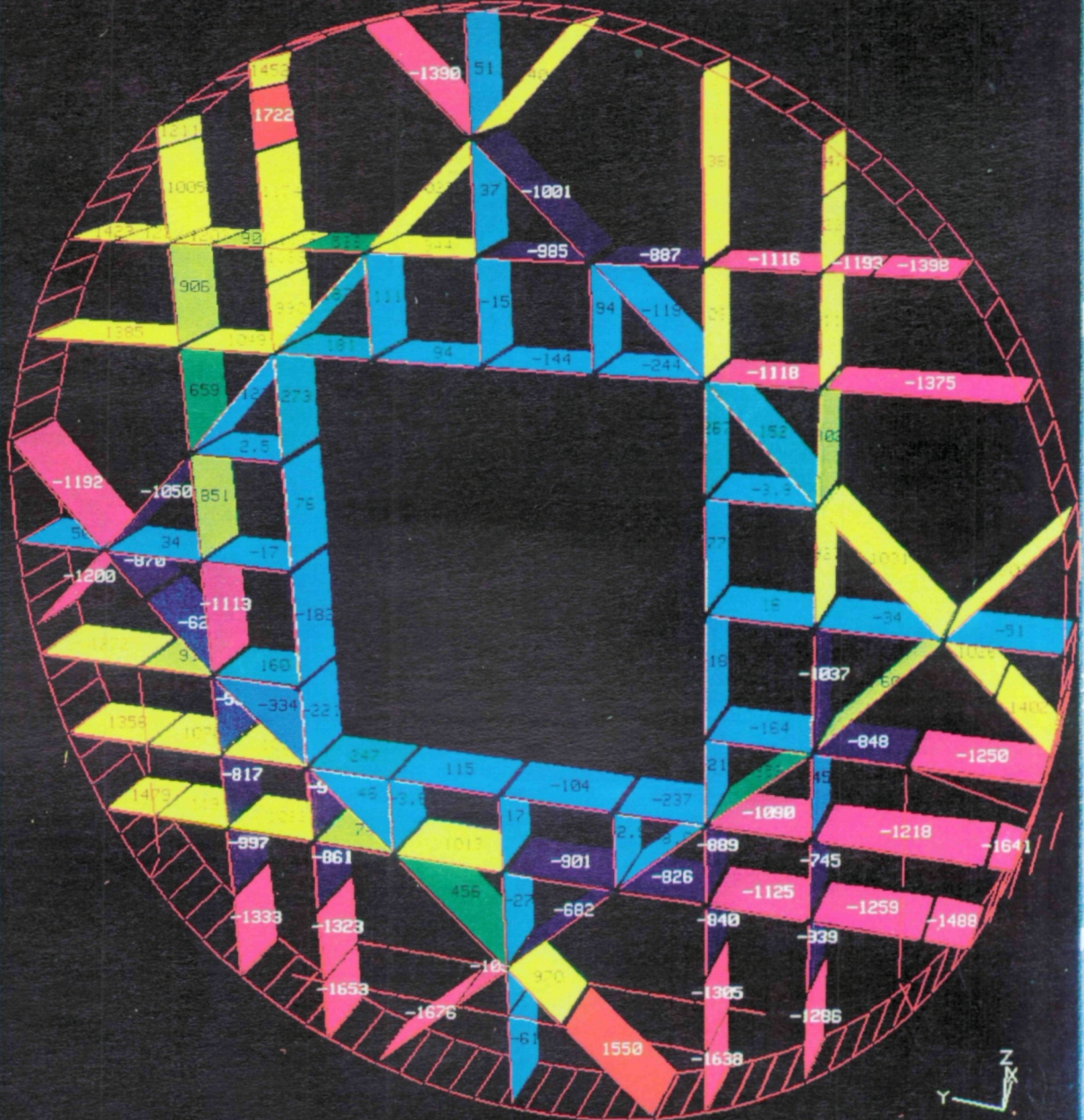
Command Input
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FILE: combMovJan.s
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 LDCASE: GL02_1a
 XMIN= 1759
 XMAX= 1781
 ZMIN= 90
 ZMAX= 390

STRIP PLOT File: combMovJan.s

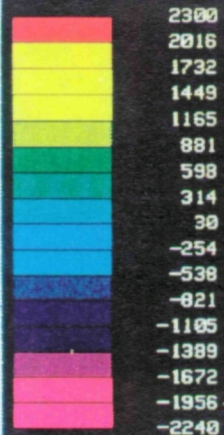
SOFIA - fwd bulkhead beam web shear flows
 (lb/in)
 GL02.1 Lateral Gust @ 40k ft / brake off



Y
 Z
 X

Forward bulkhead beam web shear flows (lb/in)
2 P (18.8 psi) Condition

**SHEAR FLOW
(LBS/IN)**



FILE: combMovJan.s

LD CASE: 2.0 PRESS

XMIN= 1759

XMAX- 1781

YMIN= -180

YMAX= 180

ZMIN- 90

ZMAX= 390

100

10

10

10

1

10

10

100

100

1

10

1



100

100

10

1

100

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1

100

10

10

100

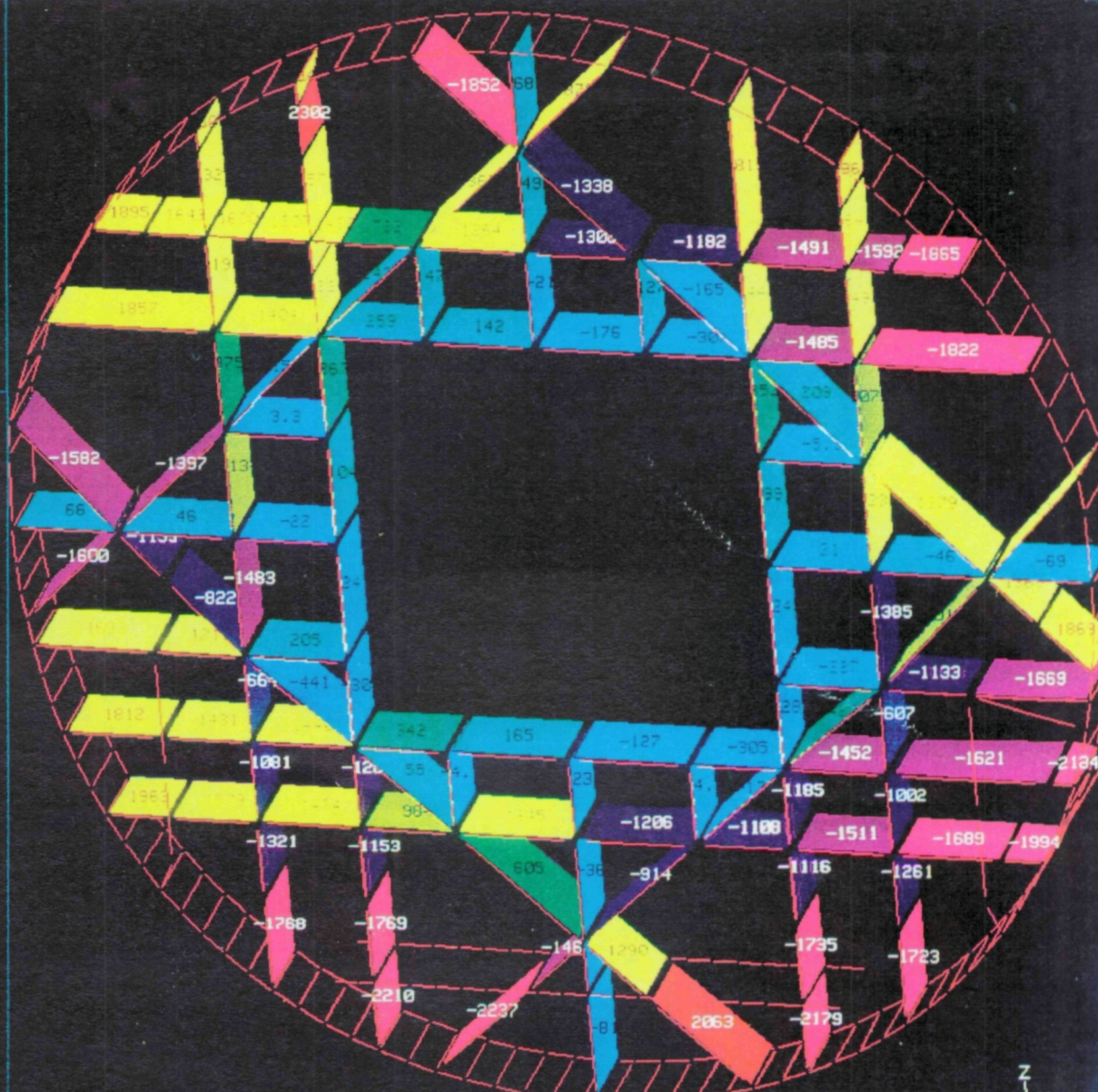
100

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10

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STRAP PLOT File: contNovJan.sf

Forward bulkhead pressure panel shear flows (lb/in)
GL01.1 Lateral Gust @ 20k ft / brake engaged
Ref GSRA report 1391-1 page 18

FILES	VIEW	HELP	QUIT
EDIT	FORMAT	SCRIPT	RENAME

VIEW | HITS | PRINT

[Home](#)
[Info](#)
[Find](#)

GEN 1 GEN 2 GEN 3 GEN 4

1990	1991
1992	1993
1994	1995
1996	1997
1998	1999
2000	2001
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2288	2289
2290	2291
2292	

MEMBRANE
XY FORCE
(LBS/IN)

	430
	379
	328
	277
	226
	175
	124
	73
	22
	-28
	-79
	-130
	-181
	-232
	-283
	-334
	-385

FILE: combMovJan.s
f

LDCASE: GL01_1+P

XMIN= 1779

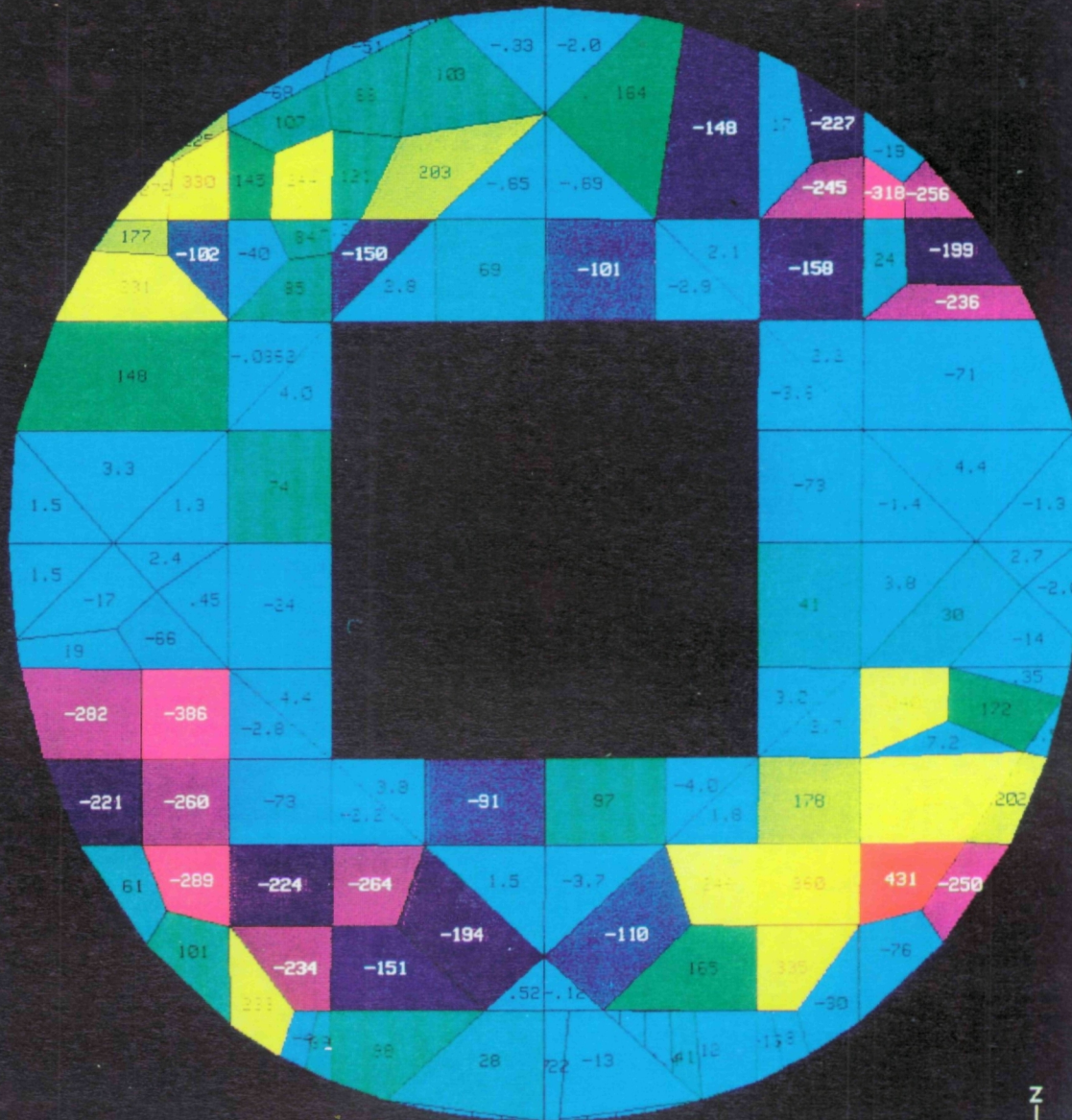
XMAX= 1781

YMIN= -150

YMAX= 150

ZMIN= 90
ZMAX= 300

ZMAX= 390





SOFIA

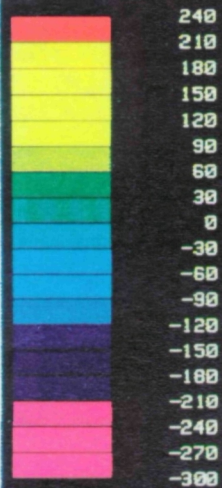
NASA

AFT BULKHEAD

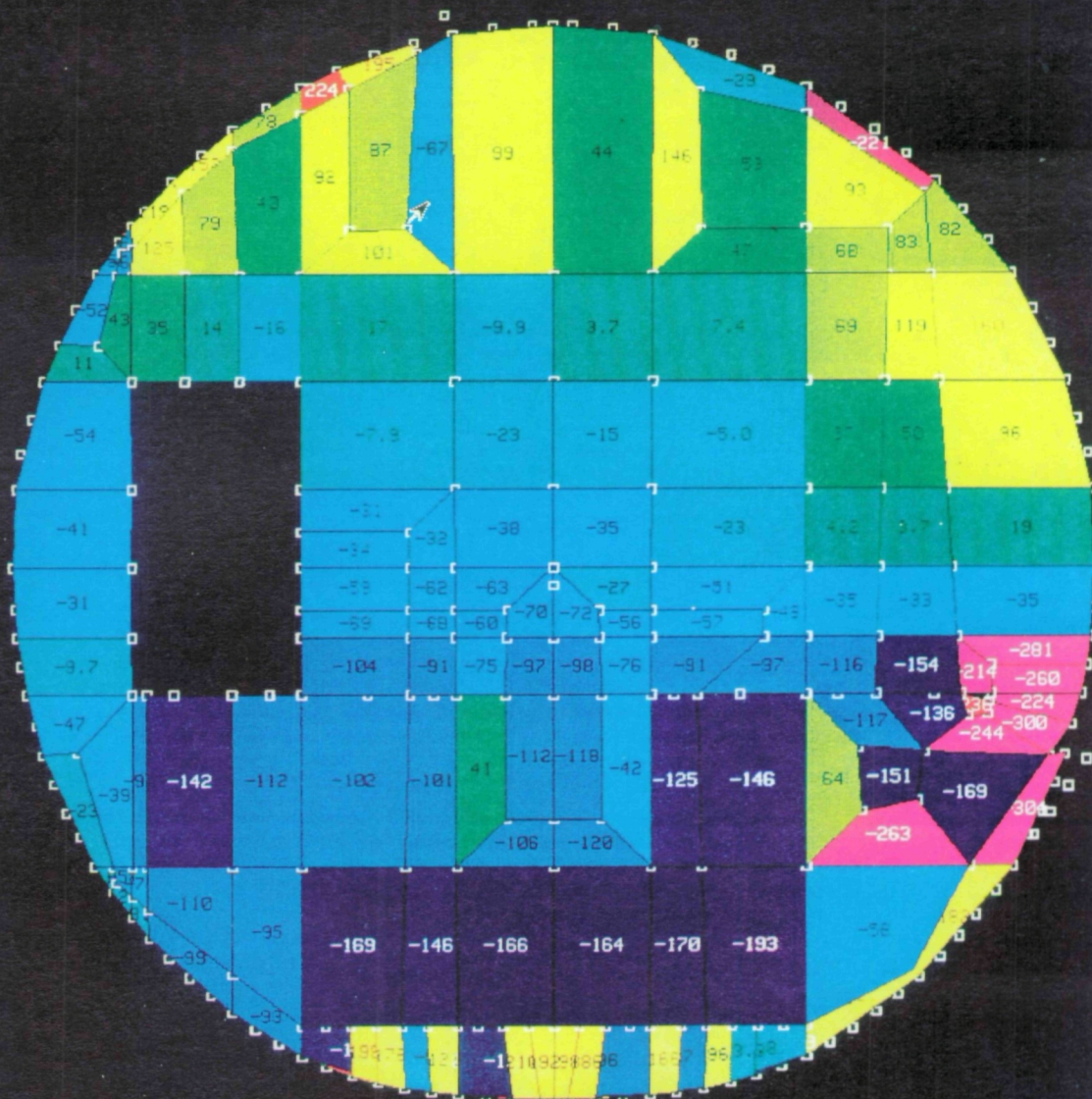
- **10 INCH DEEP BEAMS**
- **EXTRUDED PRESSURE PANEL**
- **0.063 BEAM WEB**
- **2.0 IN² BEAM CAP**
- **STIFFNESS COMPATIBLE WITH FORWARD BULKHEAD**

SOFIA - aft bulkhead shear flows
747 side-bending envelope condition

MEMBRANE
XY FORCE
(LBS/IN)



FILE: combMovJan.s
f
LDCASE: LateNz0
XMIN= 1959
XMAX= 1961



FILES RUF HELP QUIT
WIND RESET SCOPY REDRAW

MEMBRANE

VIEW LIMITS FONT

ITEM INFO FORD

IDENTER CENT C CENT I CENT Z

MOVE X ZOOM R

WSPY INT LO

Command Input:

AREA -300 200 10
AREA -300 240 10
TITLE 1 SOFIA - aft bulkhead
TITLE 2 747 side-bending envelope

Command

POSITION: MODEL SCREEN

RENAME: (U)

NUMBER: C:1

SHADE: OFF

STENCILS: OFF



SOFIA

NASA

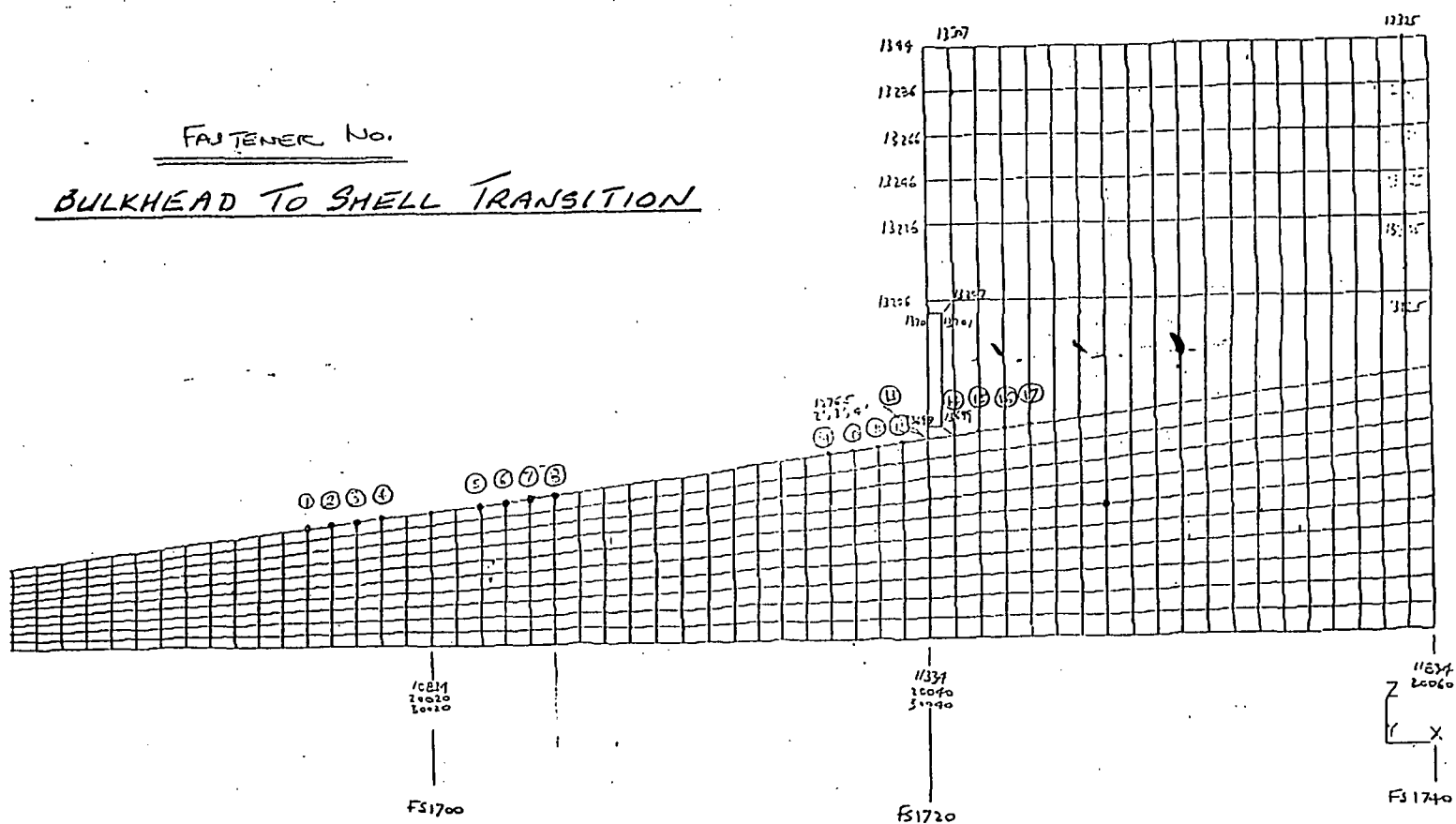
BULKHEAD TO SHELL TRANSITION

- **AREAS AND INTERCOSTAL DEPTH VARY FOR SMOOTH TRANSITION**
- **LOW STRESS LEVELS**
- **LOW LOAD TRANSFER RATE**
- **LOW STRESS SEVERITY FACTOR**
- **LONG LIFE**



SOFIA

NASA

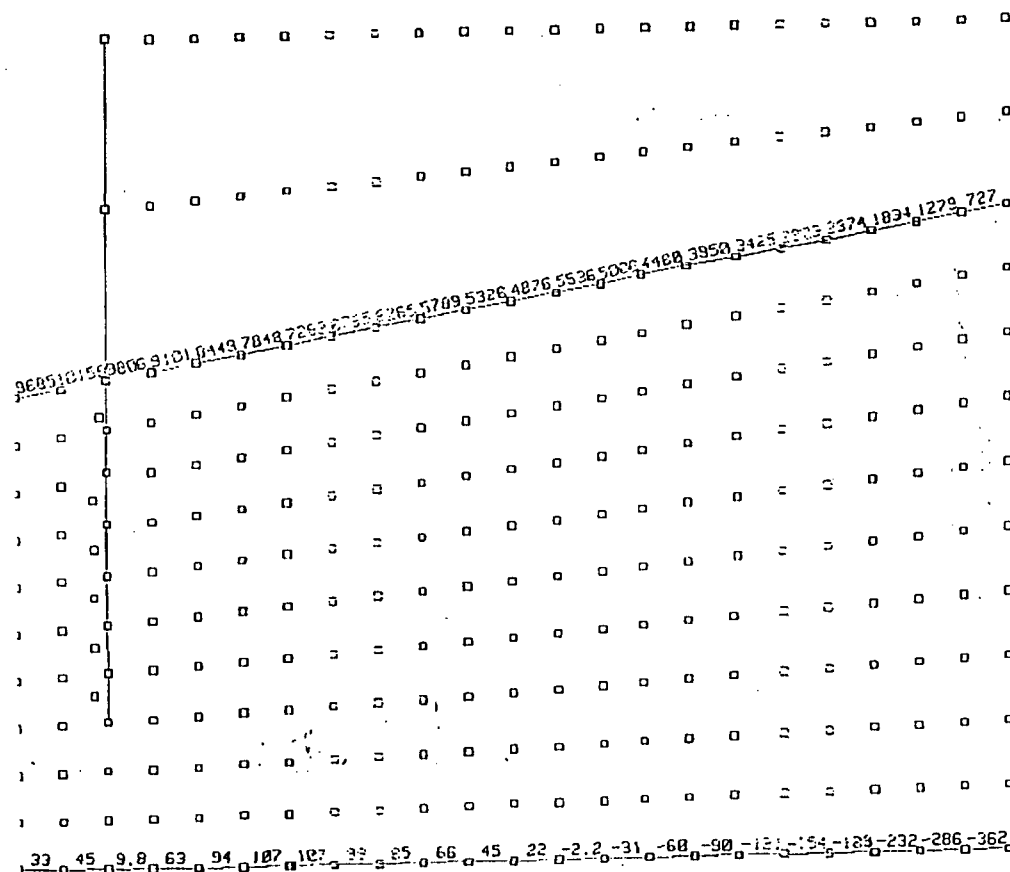




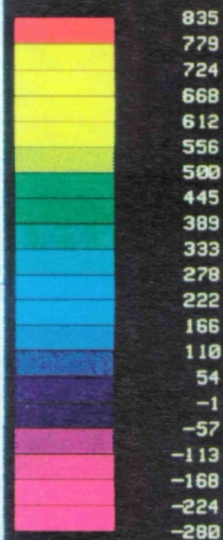
SOFIA

NASA

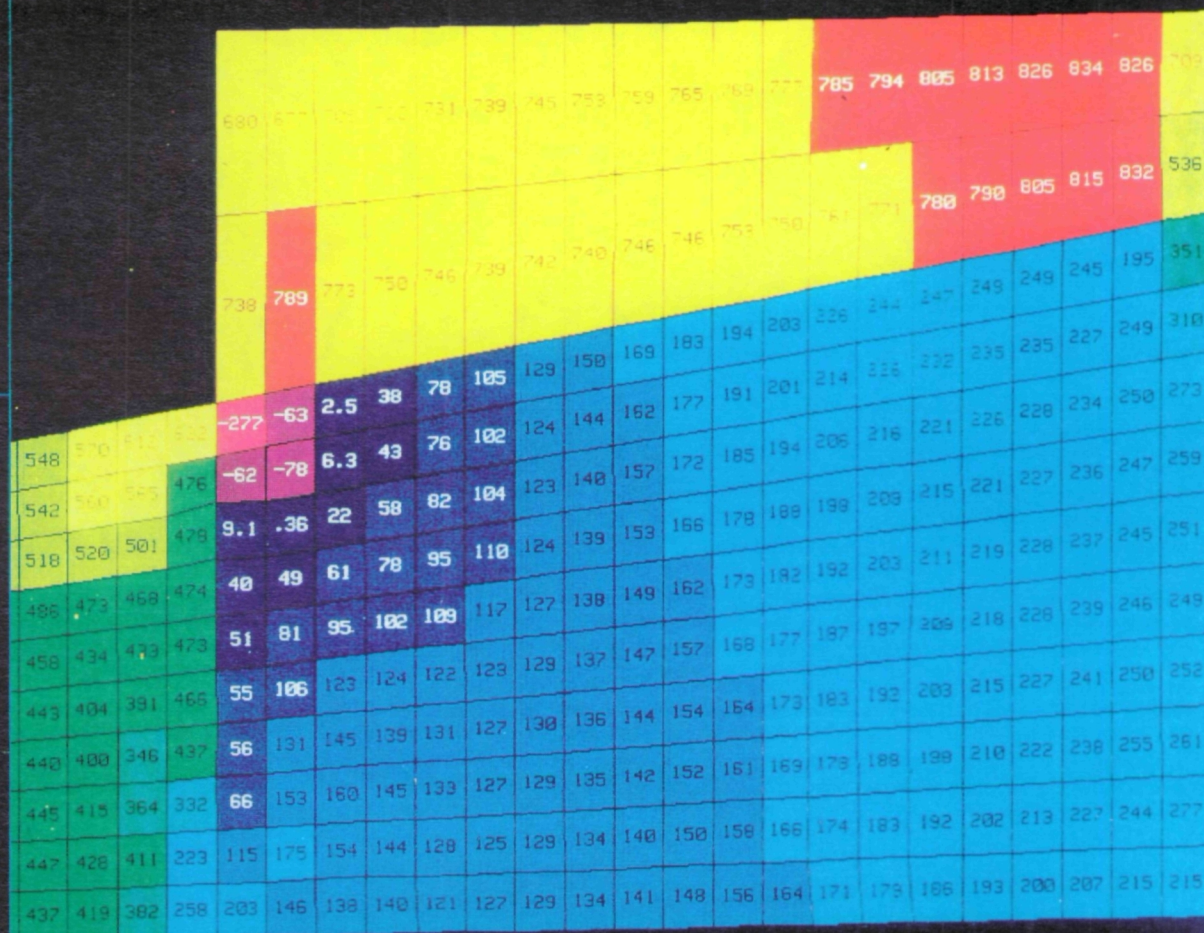
LAP AXIAL STRESS BULKHEAD TO SHELL TRANSITION



Z

Bulkhead Joint Web Shear Flow
Aft PortionMEMBRANE
XY FORCE
(LBS/IN)

FILE: joiIntegCa_0
4.sf
LDCASE: Pvalve
XMIN= 1680
XMAX= 1740
YMIN= 74.5
YMAX= 75
ZMIN= 90
ZMAX= 130



Z
X



SOFIA

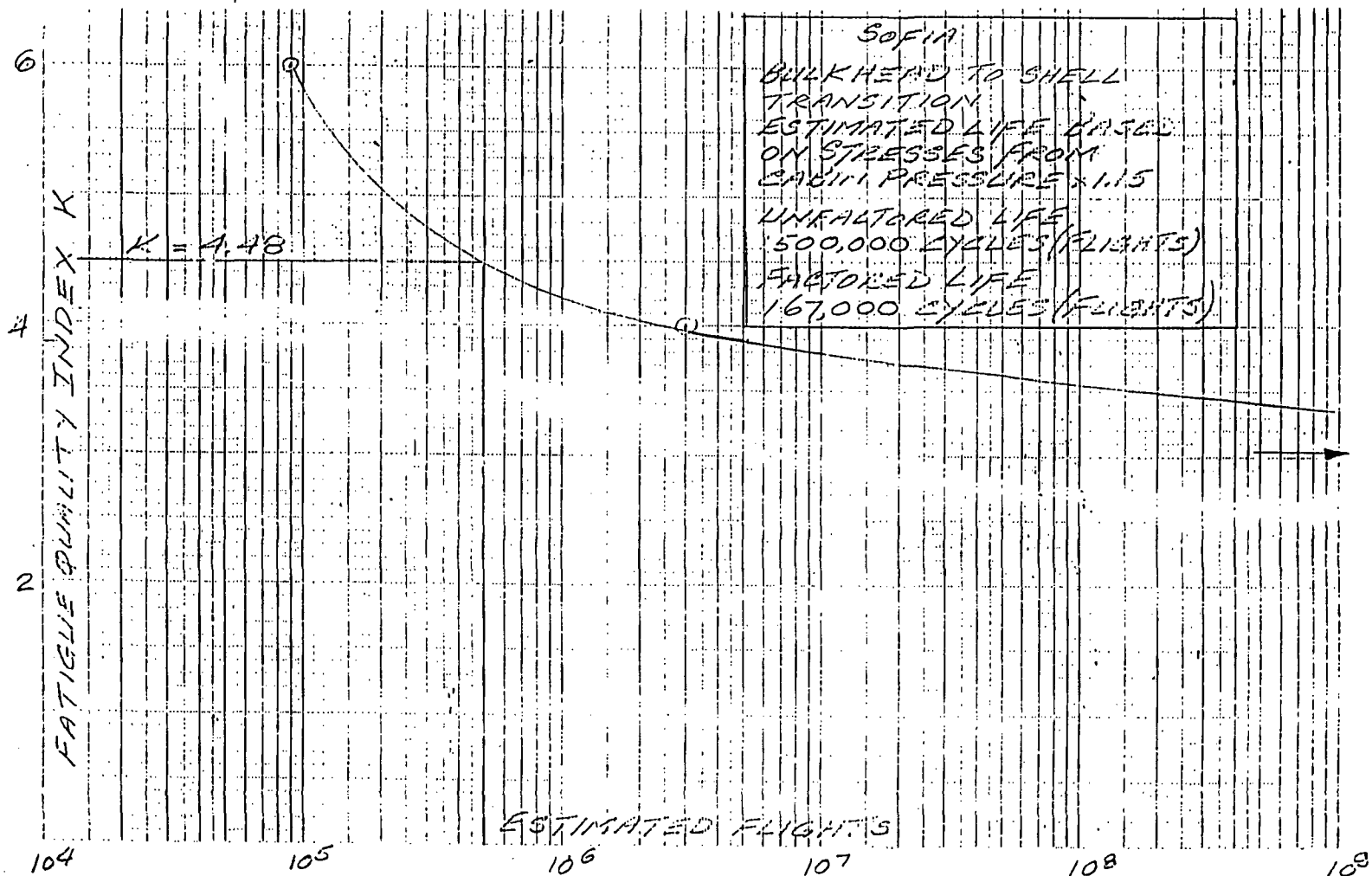
NASA

	Elem	Area	Load	Stress	Fastener Load	
Beam	23667	0.49	730.54	1490.91	94.89	
Beam	23668	0.49	825.04	1683.76	94.50	
Beam	23669	0.49	920.07	1877.69	95.03	
Beam	23670	0.49	1017.99	2077.53	97.92	
Beam	23671	0.49	1121.42	2288.61	101.43	
Beam	23672	0.49	1228.04	2506.20	106.62	Fastener
Beam	23673	0.49	1337.43	2729.45	109.39	Notation
Beam	23674	0.49	1456.26	2971.96	118.83	Ref p. 4. 21
Beam	23675	0.49	1582.25	3229.08	125.99	1
Beam	23676	0.49	1707.85	3465.00	-374.40	2
Beam	23677	0.49	881.69	1799.47	-326.16	3
Beam	23678	0.49	519.60	1060.41	-362.09	4
Beam	23679	0.49	0.00	0.00	-519.60	
Beam	23680	0.75	0.00	0.00	0.00	
Beam	23681	0.75	1399.70	1866.27	1399.70	
Beam	23682	0.75	2572.59	3438.12	1172.89	5
Beam	23683	0.75	3712.41	4949.88	1139.82	6
Beam	23684	0.75	4998.06	6664.08	1285.65	7
Beam	23685	1.00	5476.65	5476.65	478.59	8
Beam	23686	1.00	5960.81	5960.81	484.16	
Beam	23687	1.00	6446.01	6446.01	485.28	
Beam	23688	1.00	6932.76	6932.76	486.75	
Beam	23689	1.00	7419.65	7419.65	486.89	
Beam	23690	1.00	7916.38	7916.38	486.73	
Beam	23691	1.00	8420.46	8420.46	501.08	
Beam	23692	1.00	8921.65	8921.65	501.19	
Beam	23693	1.25	9436.40	7549.12	514.75	
Beam	23694	1.25	9939.14	7951.31	502.74	
Beam	23695	1.25	10443.99	8355.12	501.76	9
Beam	23696	1.25	10976.60	8781.28	532.70	10
Beam	23697	1.25	11530.80	9224.64	554.20	11
Beam	23698	1.25	12105.80	9684.64	575.80	12
Beam	23699	1.25	12697.20	10157.76	591.40	13
Beam	23700	1.25	12258.00	9886.40	-439.20	14
Beam	23701	1.25	11375.70	9100.56	-682.40	15
Beam	23702	1.25	10561.60	8449.28	-814.10	16
Beam	23703	1.25	9810.30	7848.30	-751.22	17
Beam	23704	1.25	9111.87	7289.50	-698.51	
Beam	23705	1.25	8455.67	6764.54	-656.20	
Beam	23706	1.25	7831.44	6265.15	-624.23	
Beam	23707	1.25	7236.25	5789.00	-595.19	
Beam	23708	1.25	6658.04	5326.43	-578.21	



SOFIA

NASA

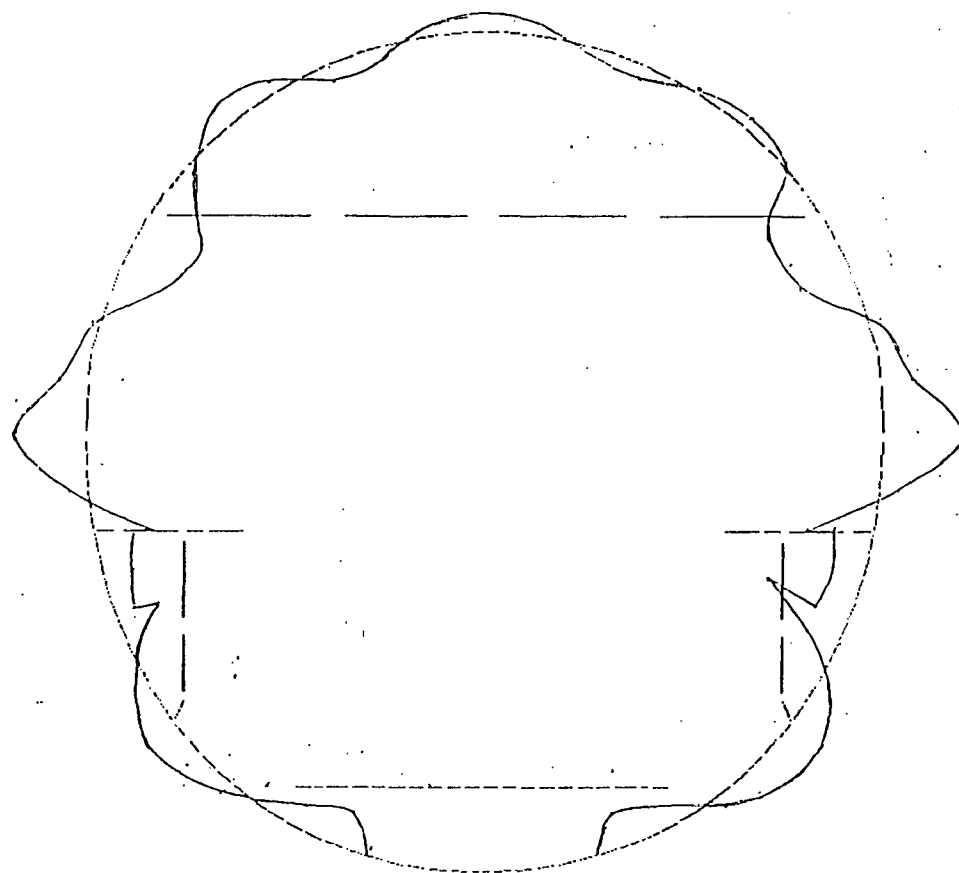




SOFIA

NASA

FS 1720 frame bending moments
I P (9.4 psi) Condition



SCALE 1" = 40000 in/lb



SOFIA

NASA

CUT-OUT SURROUND STRUCTURE

- **CONVENTIONAL CONSTRUCTION**
- **PRIMARY (EXTERNAL) AND SECONDARY (INTERNAL) LONGERONS**
- **DOUBLED UP SKIN**
- **TRIPLER FOR ADDED REINFORCEMENT AT CUT-OUT EDGE**
- **LONGERONS SPLICED WITH TENSION FITTINGS AT BULKHEAD**
- **STRINGERS SPLICED WITH SHEAR JOINT AT BULKHEADS**

[illegible]



SOFIA

NASA

Stringer axial stresses around cutout
Fuselage down-bending envelope plus cabin pressure
Ref GSRA report 1391-1 page 20

18408	24345	20496	17746	19333	21643	21383	18523	15860	13506	11395	9516	8917	7224	6025	9951	11017	8844
1139455	133775	18787	19201	19700	21110	21503	19917	16933	14482	11712	9246	7652	6243	5036	10336	3631	3335
189	34684	38736	28003	29875	25814	18308	23189	21501	19625	18261	16263	13091	10330	8407	10391	17582	20365
1257	33225	30219	29411	29336	28448	28333	23460	21105	21825	21227	20039	19757	17239	16683	12324	20369	32836
1515	31945	24800	26393	29316	13454	13370	18130	21775	23627	25159	27004	28034	33382	25831	23719	19980	31853
54069	16845	23106	21000	20026	12933	9934	17052	20861	25550	30160	34667	39678	44558	52522	36737	22573	25093
40140	32683	30600	13175	14779	8813	1351									3808	18863	3131
7	36402	32391	29390	11557	0190	5827	763									2136	11138
36	32662	29060	20044	9005	6234	2754	1323									2254	8728
14	29081	26753	24867	7560	6753	3008	-601									1905	6375
317	25735	23693	21054	7204	5859	3127	127									1541	4550
998	22703	20801	19260	6570	4643	2355	522									1037	3263
1283	19824	17974	17895	5329	6315	2073	-126									665	1973
2094	17387	15401	14491	5103	5358	3077	234									625	1060
8564	15510	13114	12082	4300	5632	3325	-144									439	570
7945	13895	11406	9467	3207	5103	2710	-160									325	227
4564	13761	10360	6315	3600	5182	1723	-841									279	107
9779	11532	8719	6607	4590	3564	1680	-101									661	108
3239	7487	9799	7976	5320	4954	1356	-041									451	163
395	7461	11055	11764	9559	5715	1480	-1461									503	36
340	14647	12043	14643	5094	5144	1935	316									768	182
350	17514	13787	14209	6154	6745	2050	-1010									548	163
25	17430	17240	16390	5314	6342	3326	.54									1128	1166
36	15647	16062	10569	8326	10237	5835	-60									994	110
17222	14103	12775	8204	13088	15974	-1265										1202	1739
15386	12680	10311	8910	16299	18344	15129	45724	28591	27377	23837	10344	13131	8940	2153	944	1784	1111
13070	6527	10587	17858	12007	5731	14541	21344	23532	19214	16677	13207	9737	5727	1275	4318	1227	564
3552	9007	13573	9561	12210	8733	6357	11599	14544	13529	10578	8720	6058	5021	3162	3255	2095	390
433	8634	7213	7823	10463	6333	2923	5875	7918	7131	5656	4506	3025	2535	2516	2318	1088	290
10	3993	3537	2760	2044	1410	-2337	-4255	-4076	-4317	-3949	-3040	-2015	-1652	-1011	-17	-658	-18
2	2084	2361	855	1005	-1286	-5235	-3519	-3094	-9488	-7814	-6330	-4534	-3131	-2138	-1583	-889	-120
1	600	1460	-825	-1823	-418	-3214	-1120	-16196	-13335	-11246	-9389	-7230	-5129	-3416	-2000	-1286	-330
-2602	-2345	-2547	-3192	-670	-1242	-16095	-18106	-15060	-14004	-12442	-11363	-10224	-8540	-6966	-5178	-3555	-1128

FILES EDIT HELP QUIT
 WINDOW RESET SCROLL REDRAW

VIEW LIMITS FONT

XVIEW DATA FIND

CENTER VIEW C VIEW I VIEW Z

MOVE I MOVE R

STOP CONT LO

Command Line

Circle 1: Left side of fuselage
 Circle 2: 747 up-load envelope
 Circle 3: 747 down-load envelope
 Circle 4: 747 up-load envelope
 Circle 5: 747 down-load envelope

Command Line

RETURN HOME SCREEN

RETURN 011

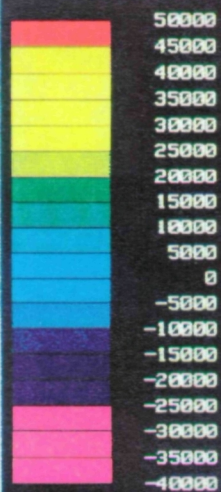
RETURN 012

RETURN 013

RETURN 014

RETURN 015

MEMBRANE
 Y STRESS
 (PSI)



FILE: combMovJan.s
 f

LDCASE: Up+P

XMIN= 1430

XMAX= 2300

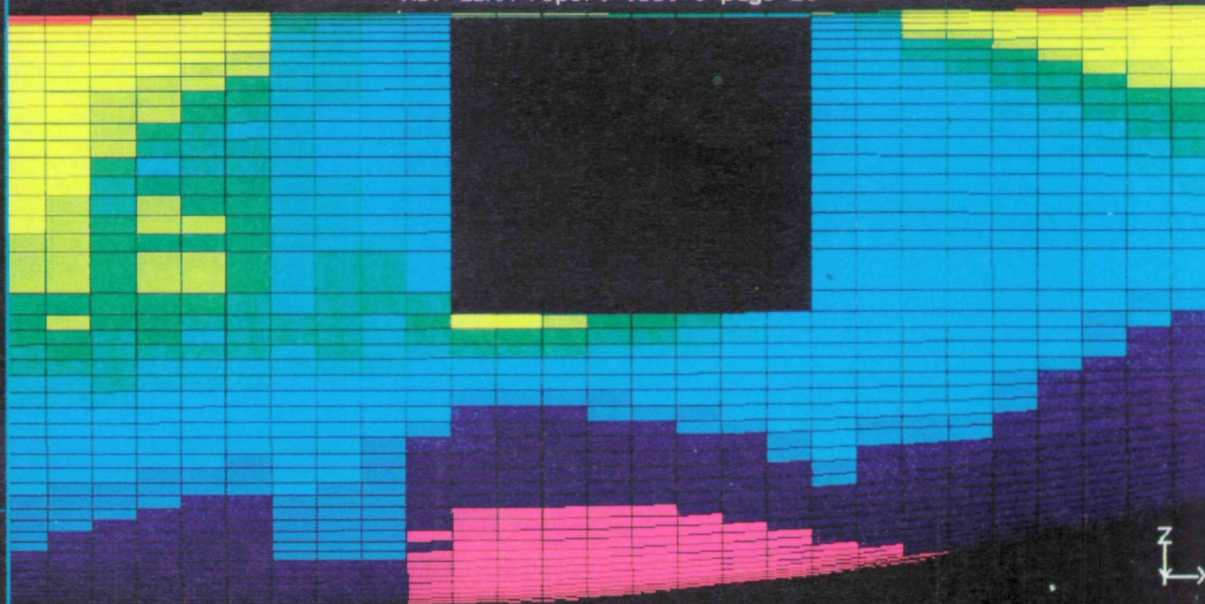
YMIN= -150

YMAX= 30

ZMIN= 90

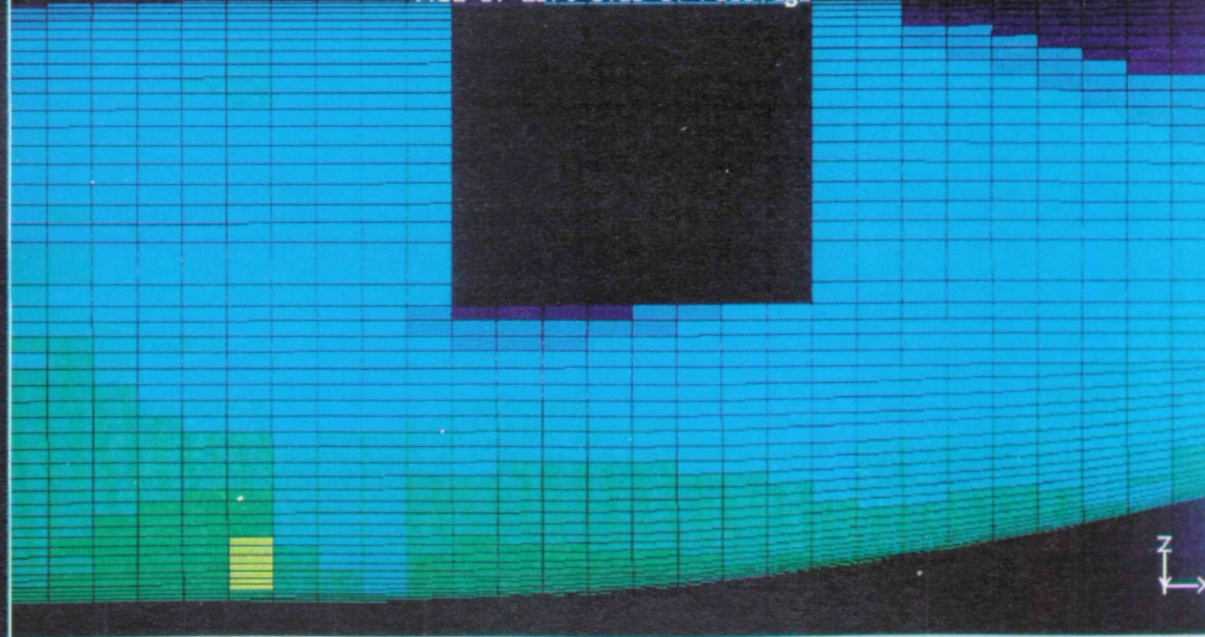
ZMAX= 390

SOFIA - Shell axial stresses around cutout
 747 down-load envelope plus cabin pressure
 Ref GSRA report 1391-1 page 21



747 up-load envelope (= -.5 x down) plus cabin pressure

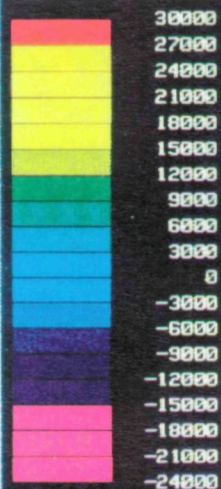
View of Left side of Fuselage



STRAP PLOT File: combMovJan.sf

SOFIA - Shell axial stresses around cutout.
747 side-load envelope (right) plus cabin pressure
Ref GSRA report 1391-1 page 21

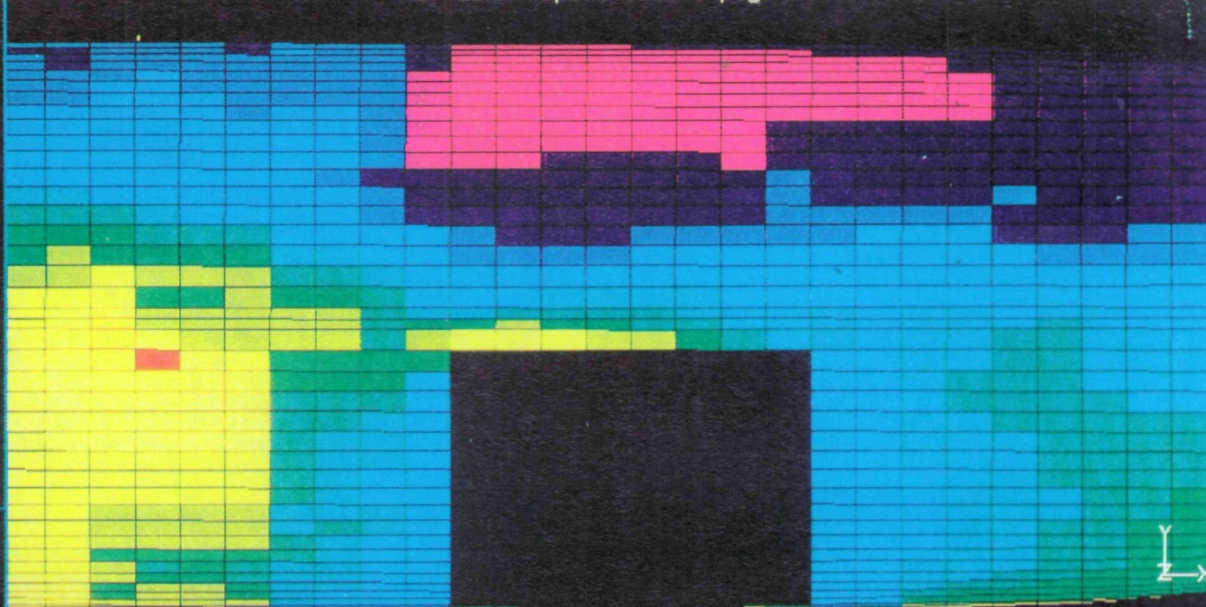
MEMBRANE
Y STRESS
(PSI)



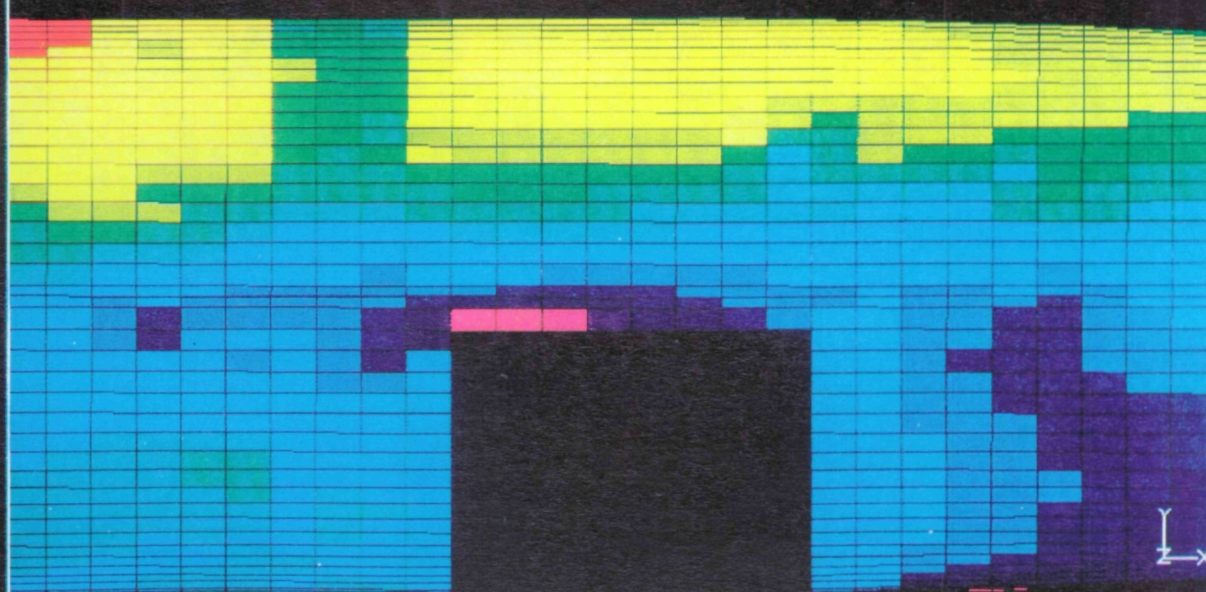
FILE: combMovJan.s
f

LDCase: OpLat0zP

XMIN= 1430
XMAX= 2300
YMIN= -150
YMAX= 150
ZMIN= 195
ZMAX= 390



747 side-load envelope (left) plus cabin pressure
View of Upper Fuselage



FILES EDIT HELP QUIT

MODIFY RESET SOURCE RETURN

MODIFY

VIEW LIMITS FRONT

VIEW INFR E100

CENTER CENTER C CENTER I CENTER 2

VIEW I VIEW R

VIEW TMT 10

Command Input:

VIEW 2 747 side-load envelope

VIEW 1 0

VIEW 1 0

747 side-load envelope (right) plus cabin pressure

747 side-load envelope (left) plus cabin pressure

747 side-load envelope (left) plus cabin pressure

747 side-load envelope (left) plus cabin pressure

747 side-load envelope (left) plus cabin pressure

747 side-load envelope (left) plus cabin pressure

747 side-load envelope (left) plus cabin pressure

747 side-load envelope (left) plus cabin pressure

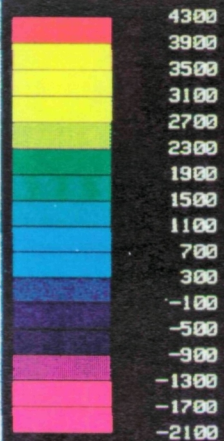
747 side-load envelope (left) plus cabin pressure

747 side-load envelope (left) plus cabin pressure

STRAP PLOT File: combMovJan.sf

SOFIA - Shell structure shears around cutout
due to 747 side-load envelope
Ref GSRA report 1391-1 page 21

MEMBRANE
XY FORCE
(LBS/IN)



FILE: combMovJan.s
f

LDCASE: LateNz0

XMIN= 1430

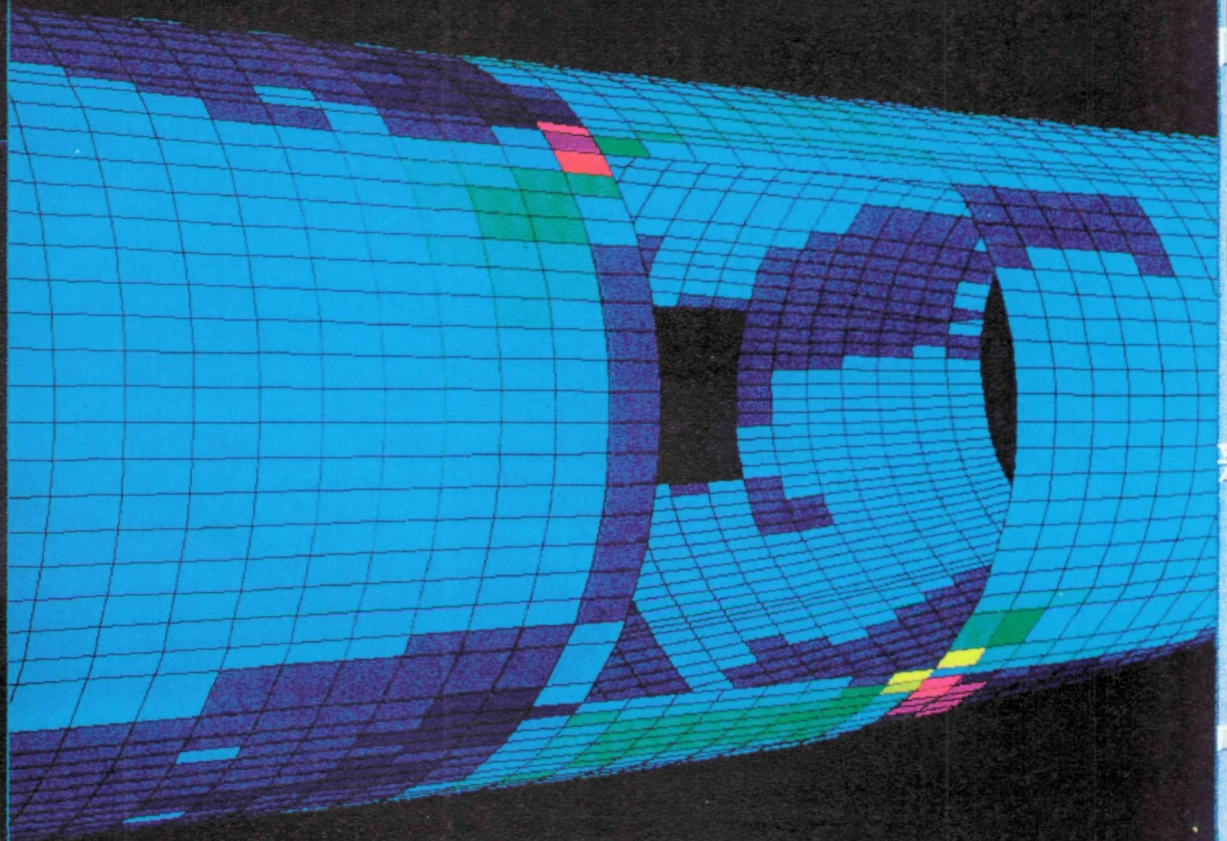
XMAX= 2300

YMIN= -190

YMAX= 190

ZMIN= 90

ZMAX= 390



FILES: FILE: HELP: QUIT:
WINDOW: RESET: SCOPY: REDRAW:

VLEN: LIMITS: FMT:
XLEN: INFO: FIND:

CENTER: CEN: C: CEN: I: CEN: Z:

MOVE: I: ZOOM: R:

WSP: TWT: LO:

Command Input:

g1w-300 390

z1w-20 390

scs-2000 4200 20

sca-2300 4300 15

Command:

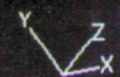
NOTION: MODEL SCREEN

RENAME: ALL

WINDOW: C:1

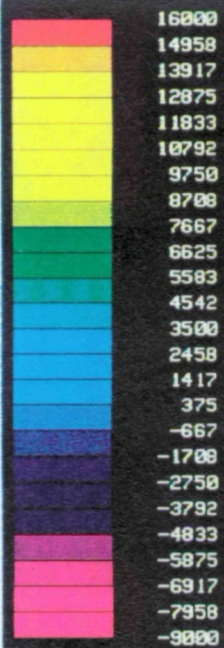
SHADE: OFF

SCHEM: OFF

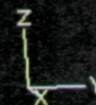
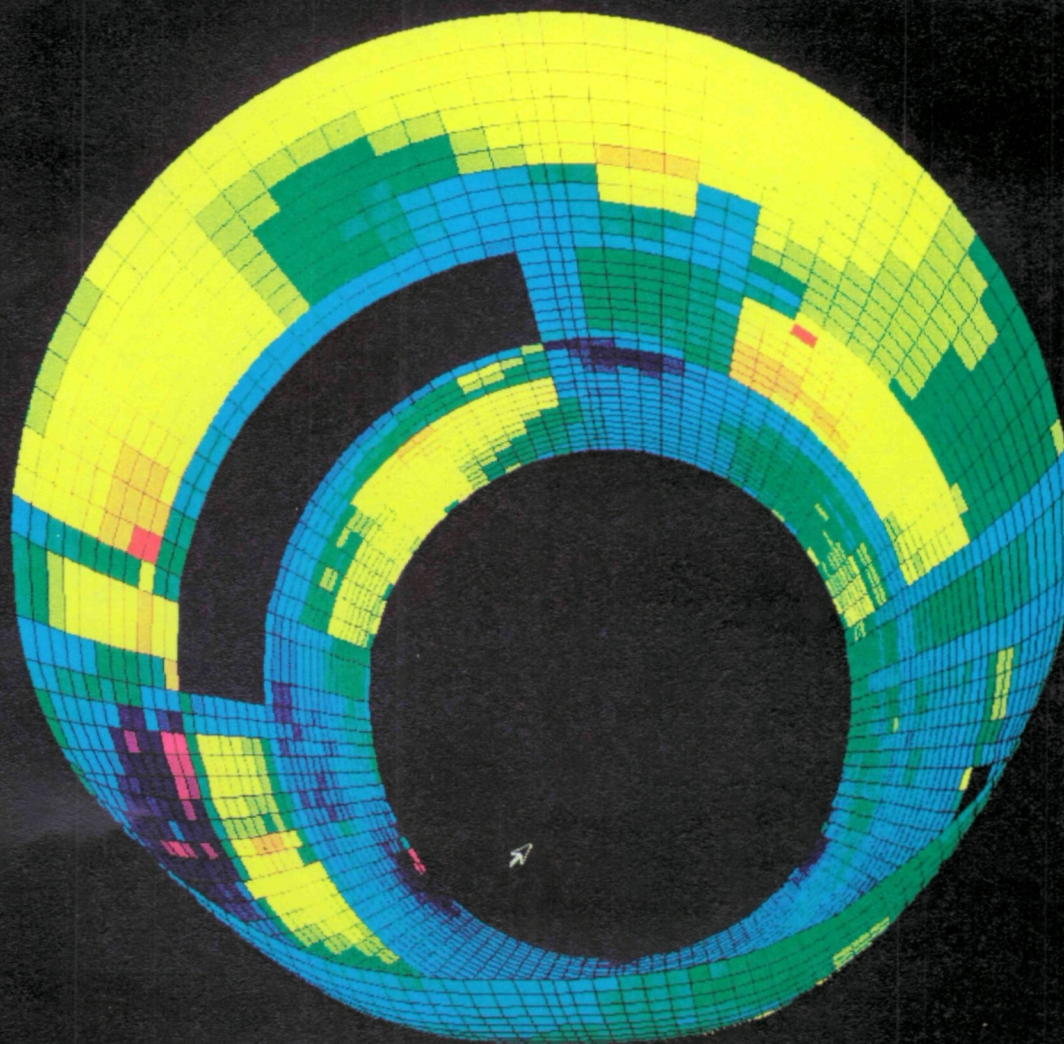


SOFIA - shell shear stresses
Max Lateral 747 Envelope Load
Ref GSRA report 1391-1 page 21

MEMBRANE
XY STRESS
(PSI)



FILE: combMovJan.s
f
LDCASE: LateNz0
XMIN= 1470
XMAX= 2300
ZMIN= 90
ZMAX= 300





SOFIA

NASA

FLOORING

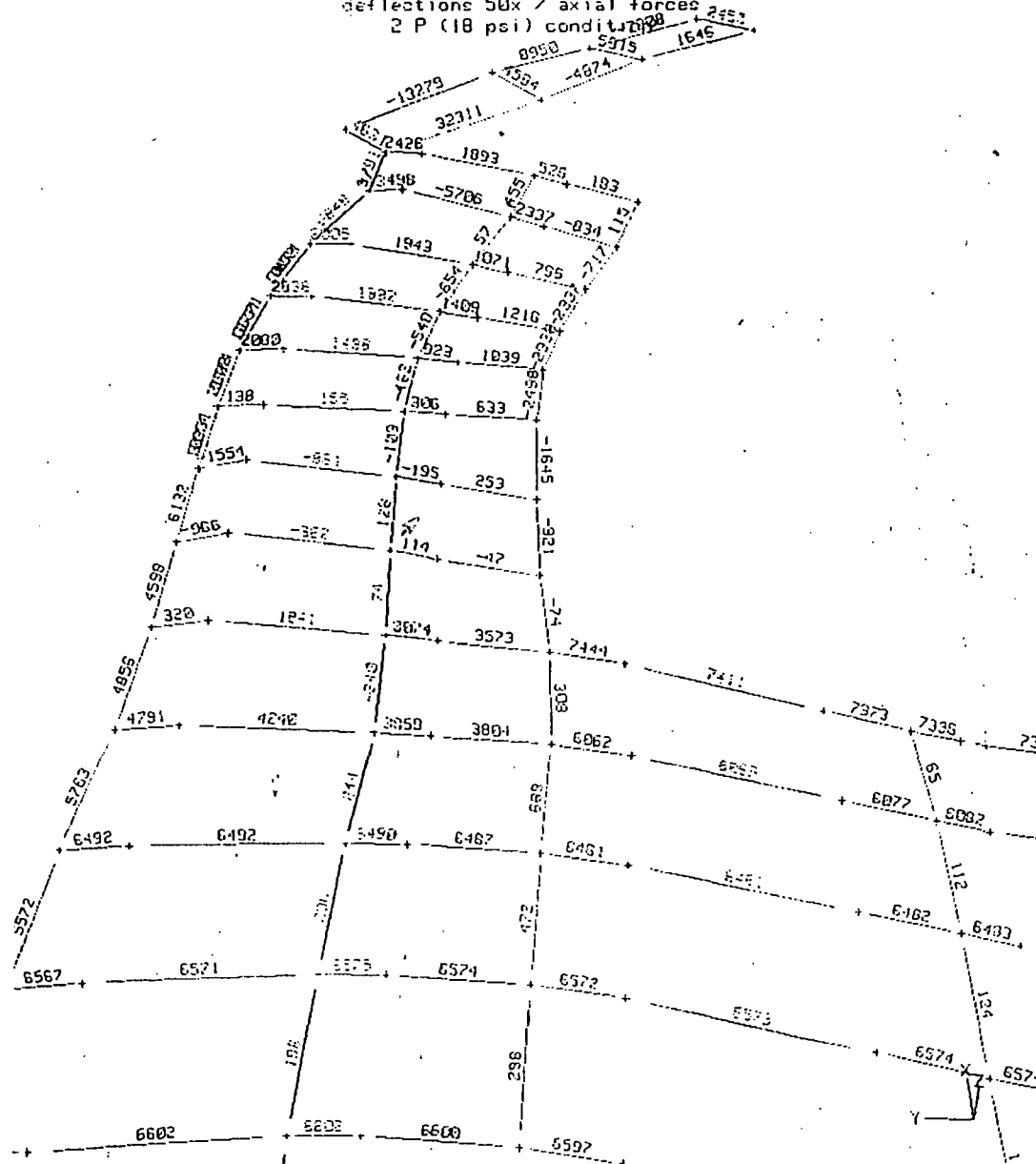
- **MAIN DECK FLOOR REMOVED IN CAVITY**
- **MAIN DECK & CARGO DECK MAINTENANCE WALKWAY**
- **CUT-OUT FORWARD OF BULKHEAD**
- **FLOORING ACTS AS BEAM TO HOLD SHELL SHAPE**
- **FLOORING DIVORCED FROM BULKHEAD TO PERMIT BULKHEAD DEFLECTION**



SOFIA

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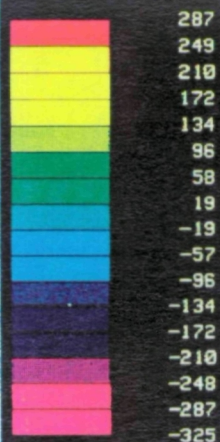
SOFIA - floor forward of fwd bulkhead
deflections 50x / axial forces
2 P (18 psi) condition



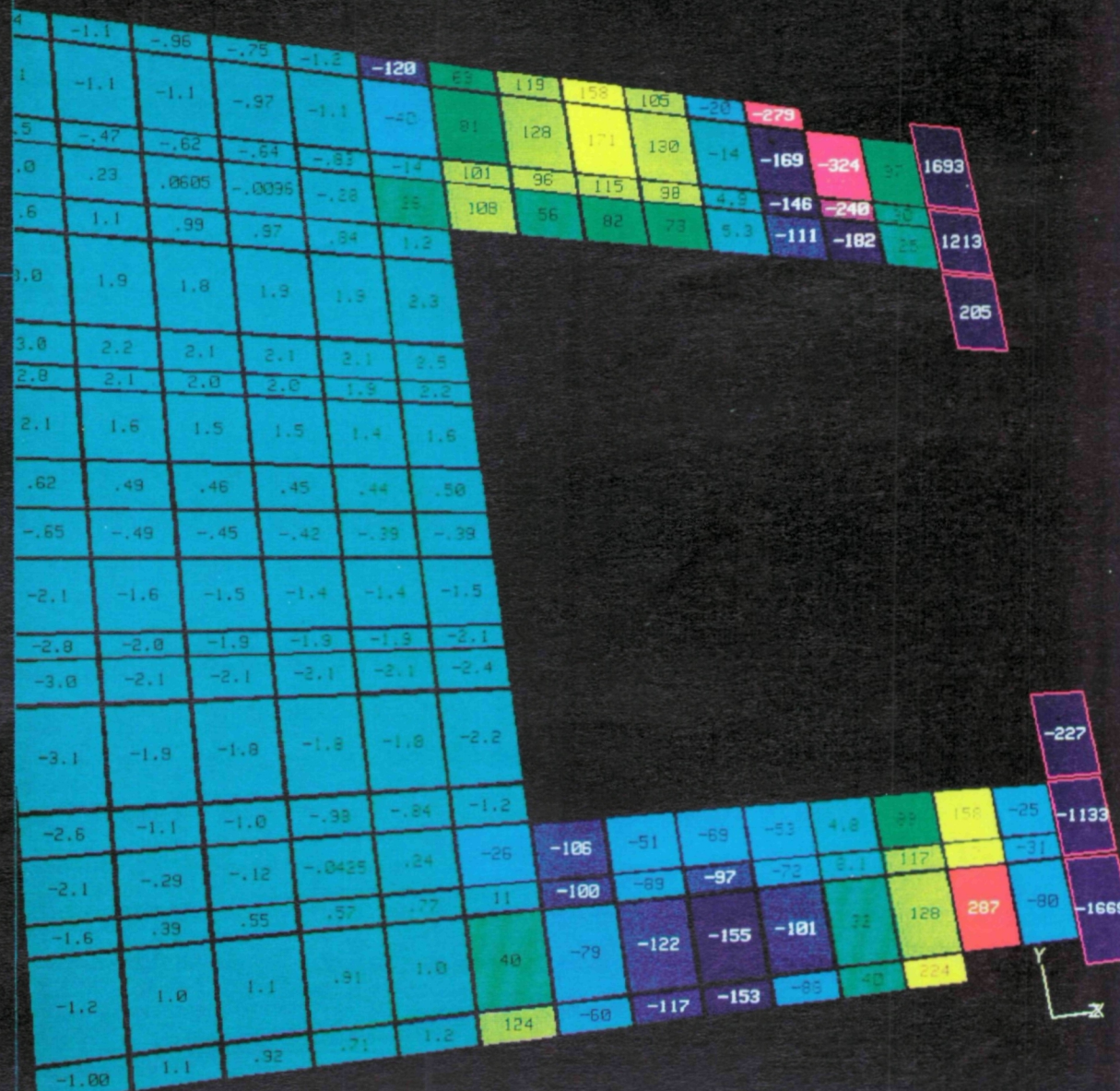
STRAP PLOT File: combMovJan.sf

SOFIA - floor forward of fwd bulkhead
shear flows
2 P (18 psi) condition

AXIAL FORCE
(LBS)



FILE: combMovJan.s
f
LDCASE: 2.0PRESS
XMIN= 1470
XMAX= 1001
ZMIN= 199
ZMAX= 200



FILES NUC HELP RCT
UNION RESET SCOPY REDRAW

VIEW LIMITS FONT
ITEM INFO FIND
CENTER CENT C CENT I CENT Z
MOVE I ZOOM R
GROUP ZMT LO

Command Input

key -325 287 18
key -325 287 18
title 2 shear flows
title 2 shear flows

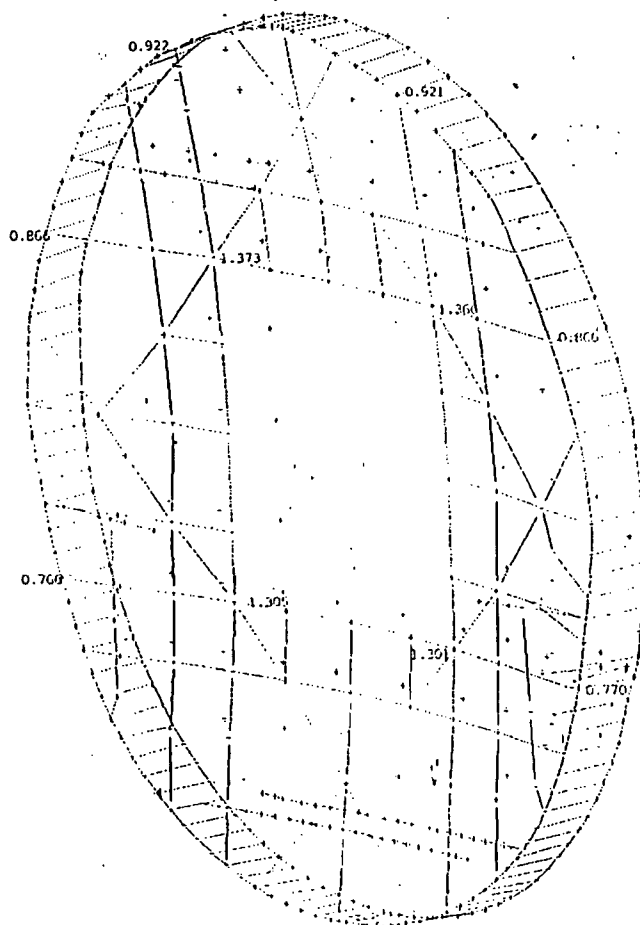
Command

NOTION: MODEL SCREEN
REMARK: ALL
REMARK: C:1
SOURCE: DTF
SOURCE: OFF

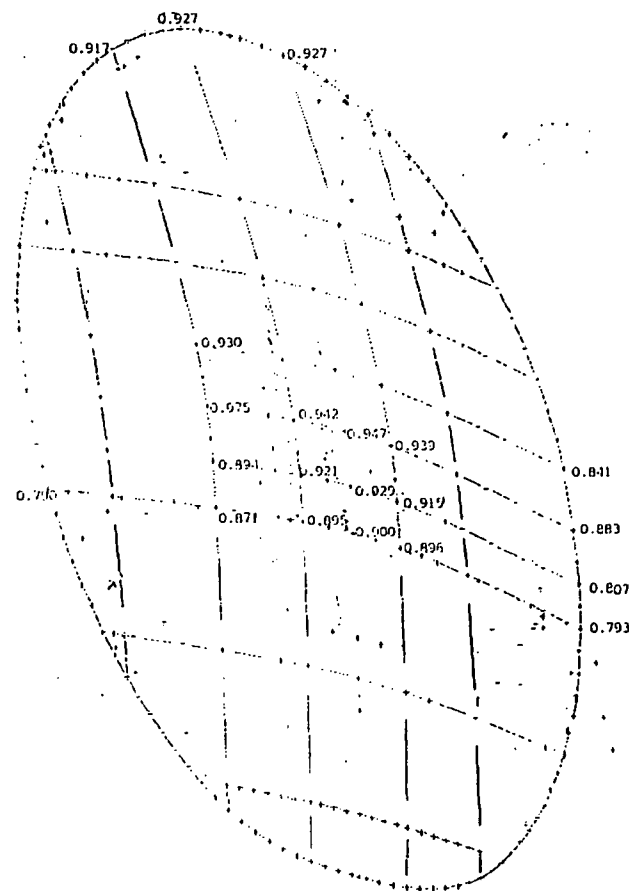


SOFIA

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Forward (Pressure) Bulkhead Deflections
9.4 psi Cabin Pressure



Aft Bulkhead Deflections
Condition 9.4 psi plus Brake Load



SOFIA

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FUTURE TASKS

- **CONTINUE DEVELOPMENT OF DESIGN IDEAS
DEvised DURING PHASE I & II**
- **REQUIRES MORE DETAILED DATA ON**
 - **TELESCOPE SUPPORT**
 - **PRESSURE SEAL**
 - **TELESCOPE BRAKE**
 - **ORIFICE DOOR & MECHANISM**



SOFIA

NASA

COST IMPACT OF VEHICLE SELECTION

● AIRCRAFT COST

- 747-SP \$10 - \$12 MILLION
- 747-100 \$2.5 - \$4 MILLION

● LOADS AND MODEL DEVELOPMENT

- 747-SP NO DATA \$5 - \$10 MILLION
- 747-SP FUSELAGE STRESS REPORT \$2 MILLION
- 747-SP FUSELAGE STRESS & LOADS REPORT \$1 MILLION
- 747-100 \$300,000